



Prevention and management of heat-related illness at mass gatherings

Systematic reviews

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**World Health
Organization**

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Declaration of interest

All external contributors to the External Expert Group and External Review Group completed a WHO declaration of interests form in accordance with WHO policy for experts. The declarations of interest and the results of a web-based search for each member were reviewed by the WHO staff and the WHO Ethics Office was consulted when necessary.

Abderrezak Bouchama is currently a “co-inventor of patent(s) related to (i) a molecular diagnostic assay for heatstroke and (ii) a thermoregulatory cooling system conceptually described as an ‘artificial hypothalamus’. These technologies are designed for potential use in clinical heatstroke management settings, including severe heat exposure contexts”. This may be perceived as a conflict of interest and therefore, he did not comment on heatstroke diagnostics and clinical heatstroke management.

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Medical staff are stationed at a first aid point during the closing ceremony of the 33rd Southeast Asian Games (SEA Games) at Rajamangala Stadium in Bangkok on December 20, 2025. © WHO / Chanakarn Laosarakham

Abbreviations

AI	artificial intelligence
HRI	heat-related illness
ICD	International Classification of Diseases
IoMT	Internet of Medical Things
KAP	knowledge, attitude, practice
OSF	Open Science Framework
PICO	population, intervention, comparator and outcome
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROBAST	Prediction model Risk of Bias Assessment Tool
PROGRESS+	place of residence, race/ethnicity, occupation, gender/sex, religion, education, socioeconomic status and social capital
ROBINS-I	Risk of Bias In Non-randomized Studies – of Interventions
SR1	systematic review 1
SR2	systematic review 2
SR3	systematic review 3
SWiM	synthesis without meta-analysis
WBGT	wet bulb globe temperature
WHO	World Health Organization

Executive summary

Extreme heat is an increasingly important threat to health and operational continuity during mass gatherings. Climate change is increasing the frequency, duration and intensity of heat exposure, while high crowd density, prolonged outdoor activity, restricted movement, inadequate access to cooling areas or safe water, and diverse population vulnerabilities can amplify risk in event settings, particularly in urban contexts. Consequently, heat-related illness is no longer a peripheral planning issue. Rather, it is a core public health and service-delivery concern that can affect attendees, volunteers, workers and security personnel during mass gatherings and can challenge local health systems. While athletes and competitive participants also face profound exertional heat stress, their protection falls largely within the established purview of specialized sports medicine and international sports federation guidelines. Therefore, this report focuses explicitly on the massive populations of spectators, volunteers, non-athlete workers and religious pilgrims exposed to heat stress in settings with limited medical and heat-mitigation infrastructure, whose heat vulnerabilities are uniquely driven by crowd dynamics and diverse demographic factors. Ultimately, this report was developed to address the need for stronger synthesized evidence on how heat-related illness can be prevented and how heat strain can be minimized during mass gatherings.

The report synthesizes findings from three systematic reviews conducted using “population, intervention, comparator and outcome” (PICO) frameworks. These reviews examined: cooling infrastructure, cool rest zones, cooling breaks and hydration practices; integrated early warning, crowd and capacity management, mobile applications and dynamic heat sensing; and visitors’ knowledge and perception, behaviour, vulnerability identification and wearable alerts. Overall, the three reviews included 54 studies. Together, they represent mass gatherings with a cumulative attendance exceeding 70 million individuals and cover a wide range of settings, including religious pilgrimages, sporting events, music festivals, exhibitions and other large public gatherings. The report, therefore, provides a broad overview of the current evidence on structural, technological and behavioural approaches to heat stress risk management in these environments.

The first review demonstrates that the clinical burden of heat exposure at mass gatherings can be substantial. Across 36 studies analysed, nearly half a million clinical encounters were recorded. These included more than 22 000 heat-related illnesses and 1196 directly or indirectly heat-related deaths, most of which were recorded during a single extreme heat event at the 1985 Hajj pilgrimage. The burden differed markedly by event type. Religious gatherings, especially those involving older populations with a high prevalence of chronic disease, showed particularly severe heat-related morbidity and mortality. Sporting events and music festivals generally involved younger populations and lower mortality but still recorded significant numbers of heat-related medical presentations, often alongside trauma and substance-related illness. The review found that the most consistently reported and operationally prominent measure was robust on-site medical infrastructure. A review of the records of patients who visited on-site medical services showed that more than 90% were managed and discharged on-site, indicating that well-organized event medical systems can substantially reduce pressure

on hospitals and ambulance services. Environmental modifications, hydration support, active cooling protocols, effective risk communication and real-time surveillance were also identified as important, although they were less consistently reported.

The second review examined digital and operational technologies that enable the early detection of heat-related illness or provide users with alerts about potential heat-related health risks. Across 10 studies, the evidence reflected a growing interest in real-time surveillance platforms, wearable physiological sensors, predictive modelling tools, mobile applications and artificial intelligence-enabled systems. These technologies offer clear potential to support earlier detection of risk, faster operational response, and more efficient deployment of medical and other logistic resources. However, the evidence base remains limited. Most of these systems were assessed in pilot or proof-of-concept settings, often using very small and highly selected cohorts. Only a few studies demonstrated integrated systems in which real-time monitoring was explicitly linked to operational public health and medical action. Static meteorological prediction models alone were found to have limited real-world predictive value, while more comprehensive systems combining environmental and clinical data appeared more promising. Overall, the review indicates that digital innovation has been advancing rapidly, but its translation into scalable, validated public health practice for mass gatherings is progressing slowly.

The third review focused on risk communication, vulnerability identification and personalized alert approaches for vulnerable populations. Across eight studies, the review found that culturally and linguistically tailored heat stress risk communication is increasingly being used, particularly during international and religious mass gatherings, and that digital messaging modalities are generally acceptable to users. However, the evidence also showed a persistent gap between knowledge and protective behaviour. Many participants understood that heat was dangerous but did not consistently change their behaviour, seek timely care or follow advice. Importantly, the review found no empirical studies demonstrating formal pre-event vulnerability screening systems or personalized wearable alert tools linked to defined response pathways in mass gathering settings. This highlights a major gap in current practice. High-risk groups are generally identified only after they present with illness, rather than being recognized proactively before exposure. Evidence on equity, feasibility, costs and acceptability was also limited across this domain.

Overall, the findings indicate that effective management of heat stress risk during mass gatherings requires a shift from reactive response to proactive, integrated and evidence-informed prevention. Structural measures, strong on-site clinical systems, culturally appropriate communication approaches, targeted protection of vulnerable groups and real-time surveillance should not be treated as separate interventions, but as complementary components of a coordinated, layered public health strategy. The report also identifies important research priorities, including equitable cooling infrastructure, intervention strategies for chronically hot environments, operational integration of early warning systems, effective identification of vulnerable attendees, validation of wearable alerts and development of crowd-sensitive response protocols. As such, this report provides an important evidence base to inform future World Health Organization guidance and support governments, health authorities and event organizers in reducing heat-related risk in a warming world.

Introduction

Mass gatherings are characterized by the concentration of people at a specific location for a specific purpose over a set period and which has the potential to strain the planning and response resources of the country or community (1). Mass gatherings therefore present some of the most complex and dynamic challenges to global public health (2). Ranging from massive religious pilgrimages to international sporting events and secular music festivals, these events routinely draw millions of individuals into highly concentrated geographical areas. Today, the operational complexities of managing these massive crowds are violently colliding with the escalating global burden of extreme heat driven by climate change (3).

The Intergovernmental Panel on Climate Change Sixth Assessment Report (4) concluded that it is virtually certain that hot extremes, including heatwaves, have become more frequent and more intense across most land regions since the 1950s, with human-induced climate change as the main driver. The 2025 Report of the Lancet Countdown on Health and Climate Change (5) reports that heat-related deaths have risen by 63% since the 1990s to an annual average of 546 000. As the frequency, duration and intensity of extreme heat events continue to rise, transforming environmental heat into one of the most significant public health concerns of the twenty-first century (6), high-density mass gathering environments are being pushed into unprecedented operational strain.

In mass gathering contexts, the risk of heat-related illness (HRI), which ranges from mild dehydration and heat exhaustion to severe and potentially fatal heatstroke, is amplified by a unique “risk signature” (7, 8). This signature is forged by the dangerous convergence of extreme environmental factors and human elements. High crowd density significantly reduces ambient airflow and restricts access to cooling zones, while prolonged outdoor exposure, intense physical exertion and inadequate hydration profoundly impair human thermoregulation (9, 10). Crucially, this vulnerability is not uniform; it is largely determined by the demographic profile of the crowd. Older adults with a high prevalence of pre-existing comorbidities, such as cardiovascular disease, renal diseases, diabetes, hypertension and mental health illnesses, face severe physiological disadvantages, as seen during the Hajj (11, 12). These vulnerabilities may be further compounded by religious fasting, which coincides with several major mass gatherings, exacerbating dehydration, electrolyte disturbance and hypoglycaemia under heat stress (13, 14). Additionally, younger festival participants face compounded risks from intense emotional and physical exertion, venue restrictions, and occasionally substance intoxication and overconsumption, as well as unsafe sexual behaviour, which further dysregulates thermoregulatory responses (7, 15, 16).

Historically, medical planning for mass gatherings has relied heavily on reactive emergency response and basic structural mitigation measures, such as deploying first-aid tents, misting fans and hydration stations. While these foundational interventions are essential, they are inherently limited by their passive nature and heavy reliance on attendee compliance (9). As event environments become increasingly extreme, the World Health Organization (WHO) has explicitly emphasized the urgent need to transition from a reactive crisis management model towards a proactive, data-driven preventive health and adaptation approach (17, 18). The rapid

evolution of the digital health ecosystem, including artificial intelligence (AI), the Internet of Medical Things (IoMT), and real-time early warning and response systems including heat-health warning systems (19), offers strong potential to predict and mitigate physiological strain before clinical collapse occurs (20). Yet, technological innovation alone is insufficient if organizers fail to actively identify and protect the most vulnerable individuals within the crowd, many of whom possess a high awareness of heat stress risk but demonstrate a dangerous “knowledge–action gap” due to deep-rooted cultural, psychological or logistic barriers (21).

This series of systematic reviews aims to support the further development and updating and/or refinement of evidence-based guidance materials and tools to integrate heat prevention and management more effectively into preparedness and response strategies for mass gatherings.

Its target audience includes governments or organizations hosting mass gatherings, other programmes and agencies involved in mass gatherings, such as decision-makers at international, national, regional and municipal levels; government officials; higher-level policy-makers; key actors such as staff at subnational and municipal levels; community health workers and nongovernmental organizations planning or managing mass gatherings.

Glossary

In this report, following terms are used:

- **Ambient heat** describes environmental conditions, including air temperature, humidity, radiant heat and wind.
- **Heat stress** describes the thermal load imposed on the body, which is shaped by ambient heat as well as activity level (metabolic heat) and clothing (22, 23).
- **Physiological strain** (sometimes called heat strain) describes the physiological response to heat stress, including increases in core and skin temperature, heart rate and sweating (22-26).
- **Heatwave** is a period of abnormally hot weather that can last from a few days to months where the maximum (typically in the day) and minimum (typically in the night) temperatures are unusually high for a specific location (27, 28).

Process

Although development of a guideline was not the aim of this work, the process described in the *WHO handbook for guideline development* (29) was followed for quality control. An **External Expert Group** is a group of experts selected in their personal capacity following WHO rules and protocols to ensure their independence and impartiality when assessing systematic review findings and drawing conclusions. When establishing the External Expert Group to review the evidence on prevention and mitigation of heat stress and HRI in the context of mass gatherings, WHO selected members in such a way as to ensure global geographical representation, gender balance, and appropriate technical and clinical expertise.

The Steering Group comprised WHO and relevant United Nations staff with expertise in the technical areas of mass gatherings, HRI, disaster medicine and systematic review methodologies, as well as WHO regional office representatives. The Steering Group members identified a systematic review team to commission the review, and decided that the research questions were to be based on the knowledge gaps identified in the WHO report titled Heat, air pollution and solar ultraviolet radiation: *Mass-gathering specific considerations and research gaps* (18). They reviewed the draft population, intervention, comparator and outcome (PICO) research questions developed by the systematic review team and also helped to identify appropriate External Review Group members. This group was composed of individuals interested in the subject of this report as well as individuals who will be affected by the recommendations (often referred to as stakeholders). The Steering Group, External Expert Group and External Review Group were consulted to make final decisions on research questions. Later, once the systematic review was completed and the draft evidence review written, they were again consulted to review the synthesized evidence findings, risk of bias assessment table, summary of findings tables and full text provided by the systematic review team. The work started in December 2025 and concluded in April 2026.

Establishing the research questions

Despite the annual participation of hundreds of millions of individuals in mass gatherings worldwide, a critical gap remains in the systematic evaluation of comprehensive, multi-tiered heat adaptation strategies (1). Recent guidance has synthesized existing literature to draft a research agenda for future evidence reviews, identifying 10 key knowledge gaps and research needs related to mass gatherings (18):

Q1. Mass gatherings present unique challenges for equitable access to cooling infrastructure. Research is needed on temporary, low-impact and low-cost cooling options deployable at scale.

Q2. Intervention strategies for mass gatherings in chronically hot environments, where risks arise not from unusual weather but from event-driven exposure among non-acclimatized populations, need to be developed.

Q3. Field-based operational data are lacking for planning optimal cool rest zones or cooling shelters during mass gatherings.

Q4. Event-specific studies are needed to evaluate the optimal duration and location of cooling breaks, the effectiveness of misting stations and culturally appropriate hydration practices for large gatherings.

Q5. Integration of early warning systems with crowd management, ticketing systems, mobile applications and event logistics is still an underexplored area.

Q6. A research-based understanding of the knowledge, attitudes and behaviour of visitors with different heat perceptions, language backgrounds and cultural practices is needed.

Q7. Effective ways to identify vulnerable attendees (e.g. via pre-registration) are necessary.

Q8. Studies are needed on the design and modus operandi (what type of alert and thresholds, who will respond and how, etc.) of wearable alerts, such as smart watches or specialized alert bracelets, and validation of their effectiveness in protecting vulnerable mass gathering attendees and workers.

Q9. Dynamic crowd heat mapping using AI or wearable sensors could offer novel approaches, but such tools remain unvalidated in real-world settings.

Q10. Crowd-sensitive response protocols should be developed and validated.

To effectively guide global event organizers and health ministries, it is important to deconstruct how heat stress is managed across structural, technological and behavioural domains. To do this in an evidence-based manner, three systematic literature reviews were conducted, grouped by specific questions in PICO format, to address these key knowledge gaps:

Systematic review 1 (SR1): Cooling infrastructure, cool rest zones, cooling breaks and hydration practices. Addressing gaps Q1, Q2, Q3 and Q4, this review evaluated the foundational effectiveness, operational feasibility and equity of structural heat adaptation, specifically focusing on cooling infrastructure, cool rest zones, cooling breaks and culturally appropriate hydration practices.

Systematic review 2 (SR2): Integrated early warning, crowd/capacity management, mobile apps and dynamic heat sensing. Addressing gaps Q5, Q9 and Q10, this review investigated the integration and scalability of early warning systems, assessing their links with crowd and capacity management, mobile applications, dynamic heat-sensing technologies and crowd-sensitive response protocols.

Systematic review 3 (SR3): Visitor knowledge, behaviour, vulnerability identification and wearable alerts. Addressing gaps Q2, Q6, Q7 and Q8, this review assessed individual-level interventions and evaluated the operationalization of precision public health through targeted vulnerability identification mechanisms, personalized wearable alert devices and heat-risk communication tailored to visitors' cultural backgrounds to improve protective behaviours.

Together, these three reviews provide a vital and evidence-based continuum, from crowd-level infrastructure to individual-level protection, necessary to establish a modern blueprint and inform future global guidance for safeguarding population health in an increasingly warming world. Details of the research questions and PICO methodology can be found in Annex 1.



Romania: Heatwaves across Europe
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Systematic review 1

Cooling infrastructure, cool rest zones, cooling breaks and hydration practices

1.1 Introduction

Mass gatherings present unique and highly complex challenges to global public health (2). Many of these events take place in regions or seasons characterized by high heat stress, and their frequency and intensity are increasingly intersecting with the growing global burden of extreme heat driven by climate change. As the frequency, duration and intensity of extreme heat events continue to rise, these high-density environments are coming under unprecedented operational strain (6). Heat stress is now recognized as one of the most important physical hazards at mass gatherings, necessitating a transition from reactive emergency response to proactive health adaptation planning (9, 30).

HRI represents a spectrum of conditions ranging from heat cramps/rash and heat exhaustion to severe and potentially fatal heatstroke (26) (Annex 2.1). During mass gatherings, the risk of these outcomes is amplified by a unique “risk signature” formed by the convergence of environmental, individual and operational factors. Elevated ambient temperatures, higher relative humidity and radiant heat can substantially increase physiological strain, while high crowd density may reduce airflow and limit access to cooler environments. Prolonged outdoor exposure, intense physical exertion, restricted movement and inadequate hydration further impair thermoregulation (9, 10).

Importantly, the burden of heat-related morbidity and mortality is strongly influenced by the demographic and cultural context of the event. Religious pilgrimages, such as the Hajj, frequently attract older adults with a high prevalence of pre-existing chronic conditions, including cardiovascular disease, diabetes, renal diseases, mental health illnesses and hypertension. Age-related declines in thermoregulatory function, such as reduced sweat gland output and altered thirst perception, make older adults highly susceptible to rapid dehydration and heatstroke, particularly in extreme desert climates (10, 31, 32). Conversely, secular mass gatherings, such as major sporting events and music festivals typically attract younger audiences. While these populations also face significant heat stress, their clinical presentations are uniquely complicated by compound hazards, including illicit substance use, alcohol intoxication, sexually-transmitted illnesses and high rates of minor trauma (15). Recreational drugs, particularly 3,4-methylenedioxymethamphetamine (MDMA) and amphetamines, can further impair thermoregulation and exacerbate the risk of fatal hyperthermia in crowded festival environments (7).

In addition to these physiological and environmental drivers, systemic and contextual factors play a critical role in shaping heat stress risk during mass gatherings. These include the availability and accessibility of cooling infrastructure, provision of safe and sufficient safe drinking water, design and implementation of heat adaptation strategies, and the effectiveness of risk communication with diverse populations (21). Cultural practices, religious obligations

(e.g. fasting, clothing requirements etc.) language barriers and differing perceptions of heat stress strongly influence the adoption of protective behaviours. Furthermore, inequities in access to resources and services can exacerbate vulnerability, particularly among marginalized or underserved groups. Without adequate planning and targeted interventions, such as robust on-site medical infrastructure, rapid active cooling protocols and passive environmental modifications, this combination of factors can lead to rapid increases in heat-related morbidity, potentially overwhelming on-site and local municipal health services (33, 34).

Despite the millions of individuals attending mass gatherings annually, a critical gap in the systematic evaluation of heat adaptation strategies remains. WHO has explicitly highlighted the urgent need for rigorous assessments of the comparative effectiveness, operational feasibility and economic costs of environmental and behavioural interventions to inform standardized global guidelines (1). Therefore, this systematic review aimed to evaluate the effectiveness and implementation of heat adaptation strategies for reducing HRI and physiological strain among individuals attending mass gatherings. By synthesizing clinical outcomes alongside feasibility, user acceptability and equity, this review provides a foundational evidence base to support WHO and global event organizers in safeguarding population health in an increasingly warming world.

An external experts group is a group of experts selected in their personal capacity following WHO rules and protocols to ensure their independence and impartiality when reviewing a draft document. When establishing the external experts group for review of this document, WHO selected members to ensure a global geographical representation, gender balance, and appropriate technical and clinical expertise as much as possible.

An external review group was also established, consisting of stakeholders who are interested in the subject or may be affected by the intervention or approach under consideration in the document, to review the document and provide feedback to reflect the real-world setting in the context of mass gatherings.

The steering group, external experts group and external review group were consulted to review the draft manuscript by email, and their feedback was incorporated by the author. Differences of opinion were resolved by consensus.

The work started in January 2026 and concluded in May 2026.

1.2 Methods

1.2.1 Study design and reporting framework

This systematic review was designed and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement (35). The methodological approach was specified in advance and structured around a PICO framework to ensure transparency, reproducibility and conceptual clarity. The review protocol was developed before study initiation and guided all methodological decisions, including eligibility criteria, screening procedures, data extraction and synthesis plans. Any deviations from the predefined methods were documented, justified and reported transparently. No amendments to the

eligibility criteria were made after the screening started. The study protocol was registered on the Open Science Framework (OSF) and can be accessed via the registration identifier (<https://osf.io/9ckjx/>).

1.2.2 Review question

The review addressed the following PICO question: Among spectators, volunteers and staff at mass gathering events held in hot or chronically hot environments (P), does exposure to enhanced cooling infrastructure, cool rest zones, cooling breaks and culturally appropriate hydration support (I), compared with standard practice (C), reduce HRI and physiological strain among spectators, volunteers and staff (O)? The full PICO framework, including population stratification, intervention typologies and outcome domains, is provided in Annex 1.1.

1.2.3 Eligibility criteria

Studies were considered eligible if they met all predefined inclusion criteria. Eligible populations included spectators, volunteers, security personnel, staff or other workers involved in mass gathering events, including but not limited to major sporting events, religious pilgrimages, cultural festivals, political demonstrations and large-scale outdoor or semi-outdoor events. Studies were required to have been conducted in hot or chronically hot environments, or during periods of elevated environmental heat exposure.

Eligible interventions comprised the implementation or evaluation of one or more heat adaptation strategies, including temporary or permanent cooling infrastructure such as misting systems, fans, mobile cooling units or cold-water immersion facilities, cool rest areas or cooling shelters, structured cooling breaks or pauses integrated into event operations, and the provision of hydration support that was free, accessible and culturally appropriate. Interventions could be implemented at the individual, organizational or environmental level, either alone or in combination.

Comparators included standard practice or lower-intensity adaptation approaches, such as reduced provision of cooling areas, absence of cooling breaks, limited access to hydration or baseline conditions before intervention implementation.

Eligible primary outcomes included clinical HRI (heat exhaustion, heat syncope, classical or exertional heatstroke, dehydration requiring medical care and collapse) and mortality. Health care utilization outcomes included emergency department presentations, ambulance call-outs and hospitalization. Studies reporting indicators of physiological strain or heat stress, including core or skin temperature, heart rate, duration of environmental exposure, or sun exposure or workload-adjusted heat stress indicators, were also eligible. Secondary outcomes of interest included utilization of on-site medical services, referral and transfer patterns, equity of access and benefit across population subgroups, feasibility of implementation, costs and user acceptability.

Only original empirical studies using quantitative, qualitative or mixed-methods designs were eligible. Publications were required to be peer-reviewed journal articles with no language criterion applied. Reviews, systematic reviews, meta-analyses, scoping reviews, editorials, commentaries, letters to the editor, conference proceedings, books and book chapters were excluded. Studies not conducted in mass gathering contexts, or not addressing heat exposure

or adaptation strategies, were excluded. Publications for which full text could not be retrieved after reasonable efforts were also excluded.

1.2.4 *Information sources and search strategy*

A comprehensive literature search was conducted in PubMed and Scopus. The search strategy combined controlled vocabulary terms and free-text keywords related to mass gatherings, heat exposure, cooling interventions and heat-related health outcomes.

Search strategies were developed iteratively and refined through pilot searches to maximize sensitivity while maintaining relevance. Boolean operators, truncation and proximity operators were used as appropriate. No restrictions were applied with respect to geographical region. The final searches were conducted on 14 January 2026, and the full search algorithms for each database are reported in Annex 2.1.

1.2.5 *Study selection and screening*

All records retrieved from the database searches were imported into a reference management system (EndNote V.21), where duplicate citations were identified and removed before screening. The remaining records were then subjected to a two-stage screening process comprising title and abstract screening followed by full-text assessment.

Title and abstract screening was conducted using ASReview, an open-source active learning-based screening tool that applies machine learning to prioritize records based on reviewer decisions (36, 37). ASReview was selected to improve screening efficiency while maintaining reviewer control over inclusion decisions, in line with emerging best practices for technology-assisted evidence synthesis. Screening decisions were based solely on titles and abstracts, with author names or journal titles concealed, to minimize potential authority or publication bias.

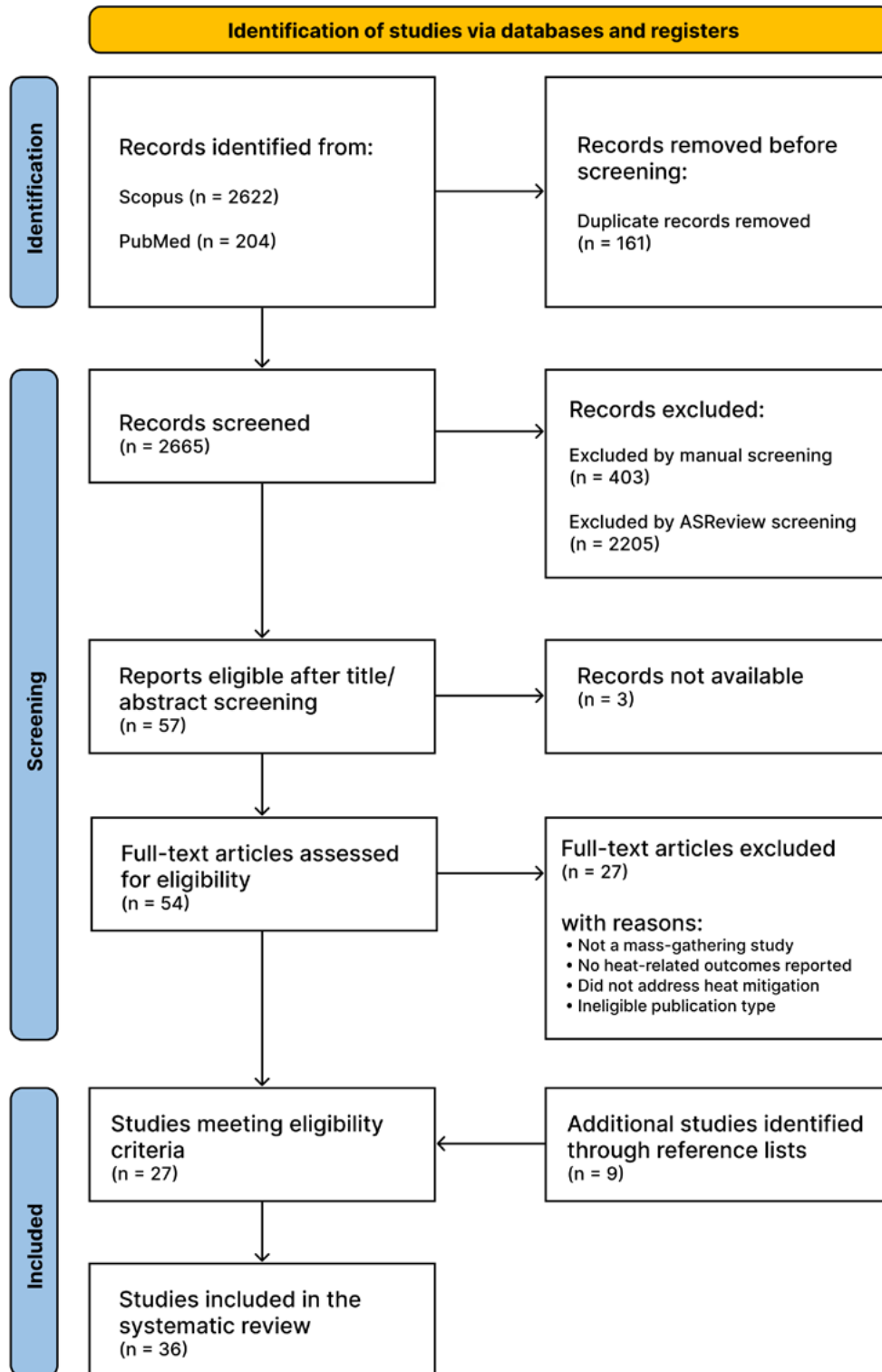
Before initiating full screening, the eligibility criteria were pilot-tested to ensure clarity and consistency in their application. To assess screening validity and reviewer alignment, two reviewers (KM; MV) independently screened a randomly selected subset comprising >15% of all retrieved records. Screening decisions from this subset were compared, and any discrepancies were discussed and resolved through consensus. The reviewers agreed on >95% of the articles. This process was used to confirm consistent interpretation of the eligibility criteria before proceeding with the remaining records.

Following validation, the remaining records were screened within ASReview, with the software dynamically reordering citations according to predicted relevance as screening progressed. A conservative stopping rule was applied whereby screening was terminated after 100 consecutive records were deemed irrelevant, consistent with recommended practice for active learning-assisted screening and with approaches adopted in recent systematic and scoping review protocols employing AI-supported screening tools (38, 39).

All records classified as potentially eligible during title and abstract screening were retrieved for full-text assessment. Full-text screening was conducted by two independent reviewers (KM; MA) against the predefined eligibility criteria. Reasons for exclusion at the full-text stage were recorded systematically and are reported in the PRISMA flow diagram (Fig. 1). If the full text of a potentially eligible study could not be retrieved through institutional access, reasonable

efforts were made to obtain the article, including by contacting corresponding authors where possible. Studies for which full text could not be obtained after these efforts were excluded and documented accordingly.

Fig. 1. PRISMA flow diagram of the study selection process for systematic review 1^a



^a The flow chart details the systematic methodology for identifying, screening and selecting eligible studies for inclusion in the review.

In addition to database screening, backward reference searching of all included full-text articles was performed to identify additional studies that may not have been captured by the electronic search strategy. Citations identified through reference list screening were assessed for eligibility using the same screening procedures and criteria as applied to database-derived records.

Any disagreements arising during full-text screening were resolved through discussion between the two reviewers (KM; MA). Where consensus could not be reached, the issue was resolved by a third reviewer (ADF). The complete study selection process is summarized in a PRISMA 2020 flow diagram (Fig. 1), detailing the number of records identified, screened and excluded at each stage, and included in the final synthesis.

1.2.6 Data extraction

Data extraction was performed independently by two reviewers (MV; MP) using a predefined and pilot-tested data extraction form. Extracted variables included authorship, year of publication, journal, country and setting of the event, study design, population characteristics, type and scale of the mass gathering, description of heat adaptation interventions, comparator conditions, reported heat-related health outcomes, and secondary outcomes related to equity, feasibility, costs and user acceptability. Discrepancies in data extraction were resolved through discussion, and where consensus could not be reached, a third reviewer (ADF) adjudicated. The complete data extraction table is provided in Annex 3.1.

1.2.7 Risk of bias assessment

Risk of bias was assessed using the Risk Of Bias In Non-randomized Studies – of Interventions (ROBINS-I) tool (40). This instrument evaluates bias across seven domains: bias due to confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes and selection of the reported result. Each domain was judged as having a low, moderate, serious or critical risk of bias, leading to an overall risk of bias judgement for each study.

Two reviewers (GG; AC) independently conducted the risk of bias assessment. When discrepancies exceeding one risk category occurred, the assessment was reviewed by a third reviewer (ADF) and resolved through consensus. Risk of bias assessments were used to inform the interpretation of findings and the strength of conclusions but were not used as exclusion criteria.

1.2.8 Data synthesis

Given the substantial heterogeneity anticipated across included studies in terms of event typology (religious pilgrimages, sporting events, music festivals, international exhibitions), population demographics, intervention components, outcome definitions and methods of measurement, a formal quantitative meta-analysis was not considered appropriate. Instead, a structured narrative synthesis was conducted in accordance with the Synthesis Without Meta-analysis (SWiM) reporting guideline (41) and Cochrane guidance on narrative synthesis (42). Extracted data were first tabulated descriptively in the data extraction matrix (Annex 3.1) to allow side-by-side comparison of study characteristics, event features, intervention components and reported outcomes. Studies were then grouped thematically according to the five prespecified domains of heat adaptation identified in the PICO framework:

1. on-site medical infrastructure;
2. active clinical cooling protocols;
3. environmental modifications and passive cooling;
4. risk communication and health promotion; and
5. operational surveillance and scheduling measures.

Within each domain, findings were synthesized narratively with supporting descriptive statistics where reporting permitted, including cumulative event attendance, total clinical encounters, absolute numbers and proportions of HRI subtypes (heatstroke, heat exhaustion, syncope, dehydration), on-site discharge and hospital transfer rates, and mortality. Aggregated counts were calculated by summing study-level denominators and event-level outcomes across typologically comparable mass gatherings (Table 1), stratified by event category (music and concerts, religious, sporting and other). Proportional outcomes were computed relative to the number of clinical encounters within each event category to mitigate the distorting effect of single very large cohorts. Secondary outcomes related to equity, feasibility, cost and user acceptability were synthesized separately in a thematic matrix. Findings were interpreted in light of the ROBINS-I risk of bias judgements, with greater narrative weight given to studies with a lower risk of bias. No subgroup or sensitivity analyses based on quantitative pooling were performed due to heterogeneity.

1.3 Results

A total of 2826 records were identified through the systematic search (Scopus = 2622, PubMed = 204). The articles were written in 32 languages: 2615 were written in English, 43 in Chinese, 29 in German, 26 in Russian, 21 in French and 19 in Spanish. The remaining 73 articles (2.6% of the total) were written in other languages. After removing 161 duplicates, 2665 unique records remained for screening. Of these, 2608 were excluded after title/abstract screening (403 manually and 2205 via ASReview). This resulted in 57 eligible reports. However, three of these reports could not be retrieved despite reasonable efforts, including direct requests to publishers and corresponding authors. Among the 54 full-text articles assessed for eligibility, 27 were excluded for various reasons including: being irrelevant to mass gatherings, lacking heat-related health outcomes, failing to address heat adaptation or being an ineligible publication type. Consequently, 27 studies met the initial eligibility criteria. Nine additional studies were identified through the screening of reference lists, yielding a final total of 36 studies included in the systematic review.

Of the 36 included studies, most ($n=23$; 63.9%) provided no information regarding their funding source or funding type. A further 10 (27.8%) studies explicitly stated that no external funding was received for the research. Consequently, only three studies (8.3%) reported an active funding source. All three of these supported studies were classified under government or charitable funding types.

The studies included in the analysis were published between 1980 and 2025. Most of these studies utilized an observational design, and all were published in English. The studies were conducted across 12 countries and included information on six broad categories of mass gathering: sporting competitions, religious pilgrimages and music festivals, as well as international exhibitions, airshows and world fairs. The mass gatherings analysed, which included specific high-profile events like the Hajj, various Olympic Games and the Ryder Cup, took place between 1978 and 2024, with event durations ranging from single-day 12-hour events to 6-month extended expositions. Collectively, the included studies reported data from 780 distinct events. The main characteristics and outcomes of these mass gatherings are reported in Annex 3.1.

The mass gatherings investigated in the studies analysed included a total of over 50 million attendees. The populations studied in the included articles were predominantly composed of event spectators ($n=19$; 52.8% articles) and religious pilgrims ($n=10$; 27.7% articles). Additional groups assessed encompassed general visitors, event volunteers, support staff and non-athlete officials, such as media personnel and organizing committee members. While the cumulative attending population across all mass gatherings analysed exceeded 50 million individuals, the specific study populations, comprising those who sought on-site medical care, underwent health surveillance or participated in cross-sectional surveys, amounted to >486 000 recorded patients. It is important to note that the vast majority of these encounters (~394 000 patients) were recorded in a single, large-scale medical mission (43) during the 2016 Hajj pilgrimage, with the remaining 35 studies accounting for ~91 000 patients.

The 36 included studies span more than four decades, with publication dates ranging from 1980 to 2025 and reported events occurring between 1978 and 2024. During this period, mass gathering heat stress management, on-site medical capacity and reporting standards have advanced substantially, while the climatic conditions under which these events were staged also changed. The majority of the HRI burden, particularly mortality, is derived from pre-2000 pilgrimage data: the 1985 Hajj cohort (44) alone accounts for 84.6% of the fatalities recorded across the articles reviewed. This concentration reflects two important features of the evidence base. First, the Hajj follows the Islamic lunar calendar and therefore migrates through the Gregorian year by approximately 11 days annually, progressing through all seasons over a cycle of roughly 33 years; second, the 1985 Hajj occurred during the peak Saudi summer, with ambient temperatures exceeding 50 °C (44), whereas Hajj seasons falling in cooler months during the same decades have been associated with markedly lower HRI burdens. This cyclical pattern means that the historical cohorts that were most severely affected consistently corresponded with years in which the pilgrimage coincided with peak summer heat. Second, the extreme environmental conditions documented in studies of the 1985 cohort, once regarded as exceptional, are increasingly representative of the thermal environment projected for contemporary and near-future pilgrimages. Recent analyses have shown that Hajj seasons returning to the summer months in the late 2020s and 2040s are expected to repeatedly exceed the “extreme danger” thresholds of heat stress under current climate trajectories (45). The historical cohorts therefore retain both scientific and operational relevance, as they represent the upper end of the severity spectrum of HRI that future mass gatherings are increasingly likely to encounter.

1.3.1 Demographic characteristics

The demographic characteristics of the populations studied varied significantly depending on the nature and cultural context of the event. For instance, studies on music festivals and sporting events (such as the Olympics, marathons and outdoor concerts) (46-51) frequently reported younger patient cohorts, often with median ages in their early twenties to thirties, and exhibited varying, although generally balanced, sex distributions. In contrast, religious mass gatherings, such as the Hajj and Sabarimala pilgrimages (43, 44, 52-59), generally involved older individuals, frequently with mean ages over 50 years and, in some cultural contexts, a higher proportion of male attendees. Consequently, these older cohorts demonstrated a notably higher reported prevalence of underlying pre-existing comorbidities. Baseline tracking in these groups revealed high rates of hypertension (ranging from 4.3% to 61.6%), diabetes mellitus (5.9% to 47.7%), obesity (14.4%) and cardiovascular disease (1.0% to 14.4%) (52, 54, 55), which are established risk factors for severe HRI (11). Furthermore, several of the largest events demonstrated a highly multinational participant population, encompassing diverse ethnic and educational backgrounds.

1.3.2 Health outcomes

The scale and severity of heat-related health outcomes reported across the 36 included studies varied significantly between the different study populations, heavily influenced by the nature of the event and the level of heat stress. In total, the reviewed literature recorded nearly half a million (n=483 906; Table 1) clinic visits, with the majority managed entirely on-site by first-aid personnel and event medical teams (91.6%; n=443 105). However, thousands of more severe cases required hospital transfers (0.9%; n=4541), often stretching the capacity of local emergency services.



Table 1. Summary of clinical encounters, heat-related illness (HRI) and medical triage outcomes across mass gathering typologies

Event category	Music and concerts	Religious	Sporting	Other	Total
Studies	(46, 48, 49, 58, 60-62)	(43, 44, 52-57, 59, 63)	(47, 50, 51, 58, 64-73)	(74-77)	
Total study population^a	19 491	417 211	21 411	28 026	486 139
Total clinical encounters evaluated	18 826	415 643	21 411	28 026	483 906
Total HRI	498 (2.6%)	19 042 (4.6%)	2 635 (12.3%)	22 (<0.1%)	22 197 (4.6%)
• Heatstroke (classical/exertional)	21	2650	0	0	2671
• Heat exhaustion, syncope or dehydration	171	15 918	2635	9	18 733
Total non-heat-related presentations	18 328 (97.4%)	394 091 (94.8%)	18 776 (87.7%)	2 859 (10.2%)^a	434 054 (89.7%)
• Medical illnesses and exacerbated comorbidities	2 004	246 839	6 521	864	256 228
• Trauma, minor injuries and dermal burns	7 765	96 373	6 328	281	110 747
Medical management/triage outcomes					
• Successfully managed and discharged on-site	17 003 (90.3%)	393 248 (94.6%)	8 634 (40.3%) ^a	24 220 (86.4%)	443 105 (91.6%)
• Transferred to hospital/secondary care	1 399 (7.4%)	1 515 (0.4%)	364 (1.7%)	1 263 (4.5%)	4 541 (0.9%)
Total reported deaths	0	1 194	0	2	1 196

^a These percentages appear low primarily due to a few large studies inflating total encounters (51, 75).

Among religious pilgrims, the burden of HRI was particularly severe, driven by prolonged outdoor exposure, physical exertion and the older demographic profile. No information on fasting was reported. Across the included Hajj studies, investigators documented more than 2600 explicit cases of heatstroke, and nearly 16 000 cases of heat exhaustion (cumulatively accounting for 19 042 cases of HRI, representing 4.6% of all medical encounters in this population) (43, 44, 52-59). For example, a single historical study reported 2134 cases of heatstroke and 15 560 of heat exhaustion, resulting in more than 1000 deaths (which constitutes 84.6% of the 1196 total deaths recorded across all the literature analysed) during the extremely hot 1985 Hajj season (44). More recent studies have continued to document high absolute numbers of HRI among pilgrims, although mortality rates were generally lower (43, 53). These pilgrims also frequently presented with exacerbations of pre-existing general medical illnesses leading to more than 246 000 presentations in this subgroup. For instance, significant numbers of secondary-care hospitalizations (n=1515) were for cases of acute cardiovascular and respiratory distress triggered by the extreme heat (43). Most of the cases of respiratory illness, however, seemed to be related to environmental conditions and air quality.

By contrast, the health outcomes observed among spectators, event staff and non-athlete officials at sporting events and music festivals showed a different clinical profile. At these events, non-heat-related presentations heavily dominated the medical burden (accounting for 97.4% of encounters at music festivals and 87.7% at sporting events). While HRI remained a primary concern, accounting for hundreds of cases of heat syncope, dehydration and exhaustion at events such as the Olympics (e.g. 1056 or 9.9% HRI cases across non-athlete populations (51)) and outdoor music festivals (e.g. 143 or 7.6% cases requiring intensive intravenous rehydration (48)), these populations also experienced a high volume of traumatic injuries. Across these events, thousands of injuries were reported, including minor lacerations, musculoskeletal sprains and blunt trauma. Overall, there were more than 7700 trauma cases at music festivals (e.g. more than 6200 (45.0%) of medical visits at a single music festival were due to trauma (49)) and more than 6300 at sporting events (over 3700 (34.8%) of medical visits were due to injuries among Olympic spectators and volunteers (51)). Additionally, substance and alcohol intoxication were recurring exacerbating factors exclusively noted in the spectator cohorts at music and sporting events, frequently compounding the physiological effects of heat exposure, and were associated with higher rates of ambulance transfers and hospital admissions.

1.3.3 *Health-related adaptation measures*

To counteract the physiological effects of heat stress, event organizers and public health authorities implemented a diverse array of health-related adaptation measures across the events studied. As summarized in Table 2, these interventions can be broadly categorized into five primary domains: on-site medical infrastructure, active clinical cooling protocols, environmental modifications, risk communication and active health surveillance.

Across the studies with extractable event-year data, the reported heat-related mitigation categories showed distinct temporal patterns over three operational eras: pre-2000 (n=10), 2000–2015 (n=13) and post-2015 (n=12). On-site medical infrastructure was near-universal across all periods (100%, 100% and 92%, respectively), reflecting its role as the operational baseline of medical planning for mass gatherings. The remaining four domains evolved non-linearly. Environmental modifications rose from 20% (pre-2000) and 15% (2000–2015) to 42%

after 2015, and risk communication showed a similar trajectory (20%, 0% and 42%). Active health surveillance increased modestly over time (20%, 15% and 33%). Active clinical cooling protocols followed a distinct pattern, appearing in 30% of pre-2000 studies, being absent from the 2000–2015 studies and re-emerging in 25% of post-2015 studies. The apparent mid-period gap corresponded with a predominance of studies of secular sporting events and music festivals in the literature covering that period. Heat-specific adaptations were less frequently described during this period, whereas the pre-2000 and post-2015 clusters were weighted towards Hajj-related and large-scale international sporting events where heat adaptation was an explicit planning focus. One study did not report an event date and was excluded from this stratification.

It is important to note that the above temporal pattern reflects the available evidence in the published literature and not necessarily progress in implementation practice in the field (i.e. an intervention not described in a published study may well have been deployed during different mass gathering events).

Table 2. Reporting frequency of heat adaptation interventions across included studies

Adaptation category	Implemented, n (%)	Not implemented, n (%)
On-site medical infrastructure	35 (97)	1 (3)
Environmental modifications	9 (25)	27 (75)
Active health surveillance	8 (22)	28 (78)
Active clinical cooling protocols	7 (19)	29 (81)
Risk communication	7 (19)	29 (81)

The most frequently applied heat adaptation strategy, explicitly reported by most of the studies (97%; n=35), involved the deployment of on-site medical infrastructure. This ranged from essential first-aid tents and roaming paramedic teams to highly sophisticated, tiered field hospitals and medical rehydration units capable of advanced life support, intravenous fluid administration and trauma care (43, 44, 46–56, 58–100). For the acute management of severe HRI, specific active clinical cooling protocols were explicitly detailed in 19% (n=7) of the studies. Specialized treatments such as ice-water immersion, forced-air cooling and proprietary body cooling units were highlighted as critical interventions, particularly for managing heatstroke at massive music festivals and the Hajj (43, 44, 46, 53, 55, 56, 59).

Environmental modifications and passive cooling strategies constituted another important preventive measure, utilized during 25% (n=9) of the events analysed. Structural and logistic interventions included the installation of air-conditioned shelters, the deployment of water misting sprays and ambient air misters, the mass distribution of free potable water and umbrellas, and even specific infrastructural adaptations, such as painting black-top walkways white to minimize thermal retention (44, 48, 49, 52, 55, 57, 63, 73, 75).

To influence crowd behaviour and encourage the use of these resources, health promotion and risk communication strategies were implemented during 19% (n=7) of events studied. Several studies emphasized the importance of targeted messaging, which ranged from real-time multilingual public announcements and digital platform alerts during the event to extensive pre-travel educational campaigns advising attendees on hydration, appropriate clothing and the early signs of heat exhaustion (44, 52, 57, 72, 73, 75, 76). Finally, operational logistics and real-time surveillance played a key role in pre-emptively mitigating heat exposure, but were only reported in 22% of the studies (n=8). These measures included continuous wet bulb globe temperature (WBGT) monitoring, altering competition start times to avoid peak daytime heat and utilizing rapid syndromic surveillance to dynamically reallocate medical personnel to high-risk zones across the event (43, 51, 63, 65, 72, 73, 75, 76).

1.3.4 Cost, feasibility and user acceptability

Equity of access was addressed or touched upon in only nine studies (25%) (50, 51, 54, 55, 58, 59, 68, 72, 73). While explicit statements outlining formal equity policies were rare, the descriptive data across several studies did imply that on-site medical and first-aid services were available to all attendees regardless of age, sex, role or country of origin (50, 51, 58, 73). To ensure equitable care for multinational attendees, some of the largest events successfully implemented remote professional translation systems and multilingual communication strategies to overcome language barriers (72), while others explicitly noted that both domestic and international pilgrims were treated equally (59). Some studies noted structural inequities and differential vulnerabilities without targeted operational interventions (55, 68). Finally, a study analysing the Sabarimala pilgrimage highlighted that gender equity could not be assessed due to strict religious prohibitions preventing women of reproductive age from attending the event entirely (54).

Reporting on costs was extremely limited (n=4) (51, 59, 64, 69). However, the available data indicated that establishing comprehensive mass-gathering medical infrastructure requires substantial financial investment. For instance, the medical care system for the 1996 Atlanta Olympics cost an estimated US\$ 4.36 million, although this was heavily subsidized with approximately US\$ 4 million in value-in-kind donations for equipment and supplies (51). To minimize internal expenses and public health costs, several events relied extensively on volunteer medical networks, hospital-supplied stocks and even personal donations of medical equipment by on-site doctors (64, 69). Furthermore, deploying physicians directly to the event sites and utilizing simple, rapid cooling methods (like iced tap water immersion) were frequently cited as highly cost-effective strategies; these approaches allowed most patients to be treated and released on-site, thereby saving time and reducing costly ambulance transfers to local hospitals (59, 69).

The feasibility of implementing these adaptation strategies, as reported in 17 studies (43, 49-51, 53-55, 59, 61, 63, 67-69, 73, 75-77), was frequently challenged by the extreme physical and logistic environments of mass gatherings. Common barriers included massive geographical footprints, uneven terrain and dense crowd conditions (even for mass gatherings held in remote or isolated locations), which severely restricted the movement of ambulances and medical personnel (54, 61, 67, 68). One study reported excessive ambient noise frequently disrupting radio communications between paramedics during a music festival, threatening to overwhelm isolated first-aid tents (61). During the Hajj, the extreme mobility of millions of pilgrims led to significant losses to

follow-up and compromised the ability of tent clinics to execute advanced cooling protocols, such as iced gastric lavage (now considered historical and no longer recommended owing to risks of aspiration and electrolyte disturbance) or continuous rectal temperature monitoring (43, 63). To maintain feasibility, organizers had to adapt by dynamically deploying emergency physicians to peripheral tents to provide direct medical oversight (61), utilizing mobile X-ray units (68) and relying on massive, well-coordinated trained volunteer workforces (50).

Finally, analysis of user acceptability highlighted a persistent friction between medical advice and attendee behaviour. Although patients treated at some events were very satisfied with the immediate care they received (54), a major ongoing problem was that many attendees refused medical treatment. Across multiple events from golf tournaments to music festivals and religious mass gatherings, a notable proportion of patients (ranging from 1.4% to more than 10%) left without being seen by medical staff or were formally discharged against medical advice (48, 52, 55, 58, 61, 68, 94). The relevant studies did not report the reasons behind this attendee behaviour. This issue was particularly pronounced at religious mass gatherings, where deep-rooted cultural and behavioural factors often led attendees to disregard health recommendations. For example, surveys revealed that large proportions of pilgrims would refuse to postpone rituals during extreme heat, chose to walk rather than use the transportation provided, frequently declined to seek urgent care for severe symptoms (55, 57) or even excluded medical personnel from certain areas due to local superstition (77). These behavioural barriers underscore the importance of culturally sensitive, pre-travel health education to improve the acceptability of heat adaptation protocols.

1.3.5 *Risk of bias*

The risk of bias assessment of the 36 included studies yielded a mixed profile. Overall, 16 studies (44%) were judged to have a low risk of bias, while the majority (19 studies, 53%) demonstrated a moderate risk, and one study (3%) was assessed as having a serious risk of bias (Fig. 2a and 2b). The domains most frequently contributing to risk of bias were unmeasured confounding factors, such as failing to control for individual exposure times or pre-existing comorbidities, and selection bias, as the data primarily captured only those attendees who formally sought care at designated medical tents. Furthermore, from a qualitative perspective, the chaotic and high-volume nature of mass gathering settings often resulted in incomplete medical record-keeping, reliance on retrospective chart reviews, and highly inconsistent clinical definitions where minor dehydration and severe heat stroke were frequently conflated into single reporting categories.

Fig. 2. Risk of bias assessment of the 36 included studies using the ROBINS-I tool (a) and summary of judgements across specific bias domains (b)

(a)

	Confounding	Selection of participants	Classification of intervention	Deviations from intended intervention	Missing data	Measurement of outcomes	Selection of the reported result	Overall	
Seiler 2025	+	+	+	+	+	+	+	+	+
Samarkandi 2025	+	+	+	+	+	+	+	+	+
Rahim 2025	+	+	+	+	+	+	+	+	+
Mercalli 2025	+	+	+	-	-	-	+	-	-
Habrat 2025	+	+	+	+	+	+	+	+	+
Collins 2024	+	+	+	+	+	+	+	+	+
Maleczek 2022	-	+	+	+	+	+	-	-	-
Imbriaco 2022	-	+	+	+	-	+	+	-	-
Almuzaini 2021	-	-	-	+	-	-	+	-	-
Nayar 2020	-	-	+	+	+	+	+	-	-
Yezli 2019	-	+	-	+	?	-	+	-	-
Ranse 2019	-	+	+	+	+	+	+	-	-
Khan 2018	+	+	+	+	+	+	+	+	+
DeMott 2018	+	-	+	+	+	+	-	-	-
Abdelmoety 2018	+	-	+	+	+	+	+	-	-
Ho 2014	+	+	+	+	+	+	-	-	-
Chia 2011	+	+	+	+	+	+	+	+	+
Yazawa 2007	+	-	+	-	-	+	+	-	-
Olapade-Olaopa 2006	+	+	+	+	+	+	+	+	+
Lukins 2004	+	+	+	+	-	+	+	-	-
Griffith 2004	+	+	+	+	X	X	+	X	X
Feldman 2004	+	+	+	+	-	+	+	-	-
Grange 2003	+	+	+	+	-	+	+	-	-
Seraj 1991	+	+	+	+	+	+	+	+	+
Gustafson 1987	+	+	+	+	+	+	+	+	+
Baker 1986	-	-	+	+	+	+	+	-	-
Pons 1980	-	-	+	+	-	+	+	-	-
Dutch 2008	+	+	+	+	+	+	+	+	+
Ghaznawi 1987	-	+	+	+	+	+	+	-	-
Grange 1999	+	+	+	+	+	+	+	+	+
Khan 2017	+	+	+	+	+	+	+	+	+
Nouhi 1992	+	+	+	+	+	+	+	+	+
Perron 2005	+	+	+	+	+	+	+	+	+
Tajima 2020	+	+	+	+	+	+	+	+	+
Tanaka 2023	+	+	+	-	+	+	-	-	-
Wetterhall 1998	+	-	+	+	+	+	+	-	-

+

 Low risk

-

 Moderate risk

X

 Serious risk

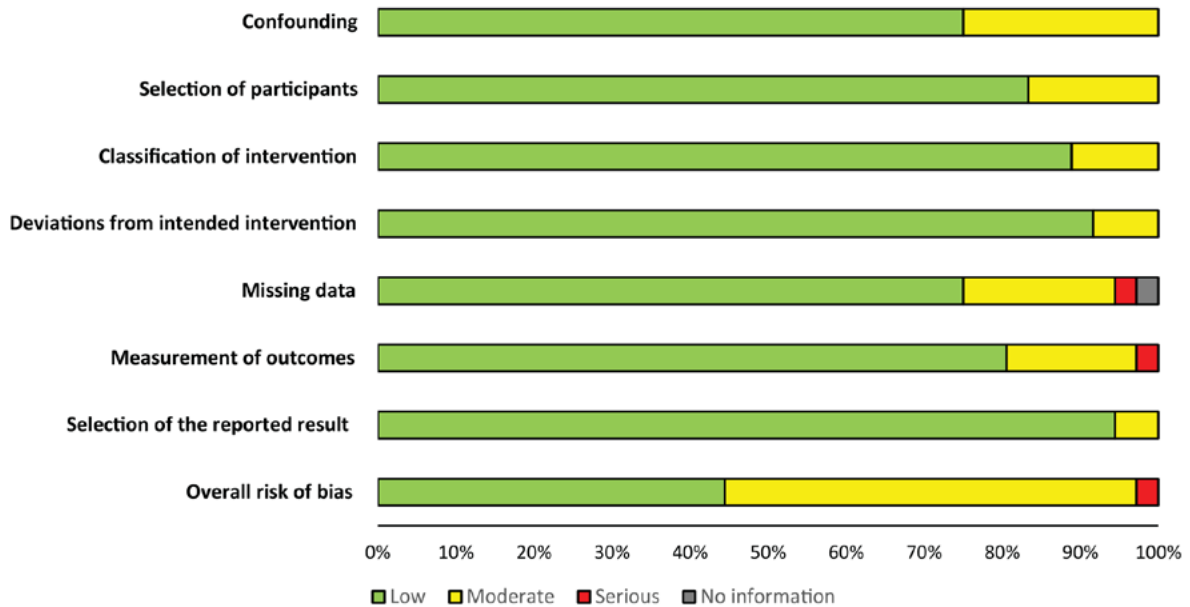
!

 Extreme risk

?

 No information

(b)



33rd Southeast Asian Games (SEA Games), Closing ceremony, Rajamangala Stadium, Bangkok, Thailand, 20 December 2025. © WHO / Chanakarn Laosarakham

1.4 Discussion

This systematic review synthesized evidence from 36 studies encompassing more than 50 million attendees to evaluate the clinical burden of heat stress and the effectiveness of heat adaptation strategies at mass gatherings. Across the literature evaluated, more than 483 000 all-cause medical encounters were recorded. Of these, approximately 22 000 (4.6%) were directly classified as HRIs, highlighting heat as a prominent, distinct driver of event morbidity. Furthermore, the included studies reported a total of 1196 fatalities. While a raw death count of this size across an aggregate population of 50 million attendees might not drastically exceed standardized background mortality rates for a similar duration, this figure does not reflect normal population attrition. Rather, the extracted mortality was highly clustered at specific high-risk events (primarily religious pilgrimages in extreme climates), with the vast majority of these deaths explicitly attributed to acute heatstroke and environmental exposure. Consequently, this represents a highly localized surge in cause-specific, preventable mortality. Our findings underscore that environmental heat stress poses a profound and complex public health challenge in these high-density settings, creating a unique “risk signature” that significantly strains both individual physiological responses and local public health capacities. The escalating frequency and severity of extreme weather events, propelled by climate change, further magnify these vulnerabilities, placing mass gathering organizers and host health systems under unprecedented operational strain (8, 47, 68, 101).

The evidence reviewed reveals a stark dichotomy in health outcomes driven by the demographic and cultural contexts of the events. Religious mass gatherings, such as the Hajj and Sabarimala pilgrimages, represent high-risk environments characterized by older populations (frequently with mean ages between 47 and 63 years). Significant pre-existing comorbidities are also a feature (most notably hypertension affecting up to 61.6% of enrolled pilgrims, diabetes up to 47.7% and cardiovascular disease up to 14.4%) (54, 57). In these settings, prolonged outdoor heat exposure and physical exertion frequently culminate in severe, life-threatening HRI, including classical heatstroke and severe heat exhaustion. This vulnerability is strongly corroborated by recent epidemiological reviews of the Hajj, which emphasize that the intersection of extreme summer heat, intense physical exertion and chronic comorbidities, particularly diabetes, which accelerates dehydration through hyperosmolar hyperglycaemic states, drastically elevates mortality risk (62, 63, 102). Additionally, age-related declines in thermoregulatory function and thirst perception make older adults highly susceptible to dehydration, which compounds physiological strain and precipitates acute cardiovascular events (11, 103). Notably, classic heatstroke in desert climates as in Mecca predominantly affects these older populations, especially those with comorbidities, emphasizing the critical need for targeted clinical vigilance and tailored prevention measures, including culturally appropriate risk communication (104).

The literature analysed reported that sporting events and music festivals typically attracted younger participants (median ages in the early twenties to thirties). While these events also generated high volumes of HRI (such as heat syncope and dehydration), the clinical profile is distinctly complicated by high rates of trauma (accounting for more than 110 000 recorded injuries) and the exacerbating effects of substance and alcohol intoxication. These findings align with the broader literature on mass gathering medicine, which confirms that while outdoor music festivals are subject to surges in HRI, the primary drivers of severe morbidity and off-site hospital transfers remain substance intoxication and minor trauma (60, 62, 105). This is

consistent with the wider epidemiological consensus that noncommunicable risks, including physical injuries and alcohol-related incidents, constitute the highest burden of disease at secular mass gatherings (2, 7, 106). These distinct profiles highlight that medical planning for mass gatherings cannot be approached with a one-size-fits-all methodology; interventions must be carefully tailored to the specific demographic, behavioural and environmental risk factors of the anticipated crowd.

A consistent finding across the included studies was the central role of on-site medical infrastructure in managing heat-related presentations. This operational feature was remarkably stable over time, being reported in 100% of studies before 2000, 100% of studies between 2000 and 2015, and 92% of studies after 2015, establishing it as the enduring baseline of medical planning for mass gatherings spanning four decades of evolving practice. The deployment of tiered field hospitals, distributed first-aid tents and specialized medical rehydration units was found to be essential across almost all included studies. Strategically stationing emergency physicians directly at the event site was repeatedly highlighted as a highly cost-effective and feasible intervention. Across the nearly half a million medical encounters evaluated in this review, 92% (n=443 105) of patients were successfully managed and discharged on-site, resulting in a remarkably low overall hospital transfer rate of just 1% (n=4541). This evidence robustly supports previous research demonstrating that the integration of higher-level care teams and on-site physicians in medical care provision for mass gatherings can reduce ambulance transfers by up to 89%, effectively shielding local municipal emergency departments from event-driven surges (58, 61, 100, 107). This approach allows advanced care, such as intravenous rehydration and rapid active cooling protocols (e.g. ice-water immersion), to be administered at the point of care, minimizing the time to definitive cooling, which is a critical factor in the survival of heatstroke patients. Rapid active cooling must be initiated immediately on-site, as delayed treatment significantly increases the risk of progression from heat exhaustion to fatal heatstroke and multiorgan failure (30, 108).

Beyond clinical interventions, passive environmental modifications (e.g. cool rest zones, misting fans, free portable water distribution (44, 48, 49, 52, 55, 57, 63, 75)) and operational strategies (e.g. dynamic WBGT monitoring and altering event schedules (51, 72, 73)) represent vital preventive measures. Indeed, the expansion of provision of cooling areas, misting systems and wide-scale safe water distribution has proven instrumental in curbing the incidence of HRI during recent Hajj seasons, despite escalating heat levels (8, 30). However, the success of these preventive strategies is heavily contingent upon user acceptability and attendee behaviour. Our review identified a persistent friction between public health advice and crowd compliance. High numbers of patients refusing care or being discharged against medical advice were noted across various events. In religious contexts, deeply ingrained cultural beliefs and the imperative to complete rituals frequently superseded personal health concerns, leading pilgrims to ignore extreme heat warnings or decline necessary medical interventions. Cross-sectional data from the 2024 Hajj further validated this behavioural risk, revealing that nearly 60% of pilgrims surveyed refused to seek urgent care for severe symptoms, and nearly 27% declined to use basic sun protection such as umbrellas (55). This highlights a critical gap in current adaptation efforts: structural interventions must be accompanied by tailored, culturally sensitive, pre-travel health promotion and risk communication, which is increasingly recognized as a cornerstone of health adaptation planning for climate change (17).

Finally, our synthesis revealed significant reporting gaps regarding the equity, cost and feasibility of heat adaptation interventions. While universal access to care was generally implied, explicit strategies to address differential vulnerabilities, particularly across socioeconomic gradients or language barriers, were rarely detailed. Furthermore, the financial burden of establishing comprehensive medical networks for mass gatherings is substantial. However, cost-benefit analyses remain almost non-existent in the literature, making it difficult for organizers in resource-limited settings to advocate for necessary infrastructure. Research highlights this as a critical gap, with studies calling for robust economic evaluations and feasibility studies for environmental interventions to better protect mass gathering attendees (18, 109).

1.5 Limitations

This systematic review is subject to several limitations. First, the high degree of heterogeneity across the included studies regarding event typologies, population demographics and the definitions of heat-related outcomes precluded a quantitative meta-analysis. The synthesized data primarily rely on descriptive and observational studies, which inherently carry a possible higher risk of bias, particularly concerning confounding variables such as baseline hydration status, acclimatization and individual behavioural choices.

Second, there is a pronounced geographical, cultural and sex/gender skew in the available literature. A disproportionate amount of the data regarding severe heatstroke and mass mortality are derived from studies of the Hajj pilgrimage (43, 44, 52, 53, 55-57, 59, 63). While these studies provide invaluable insights into extreme heat stress in older populations, particularly those with comorbidities, their findings may not be entirely generalizable to secular mass gatherings or events held in different climatic zones with different religious characteristics. Moreover, the participant populations across the evidence base were frequently skewed towards male attendees, reflecting the male-predominant demographics of several major pilgrimages and sporting events. Additionally, in some settings, data reflected cultural norms restricting female participation in survey-based or clinical data collection (e.g. gender interaction constraints at the Hajj, and the religious exclusion of women of reproductive age from the Sabarimala pilgrimage). Where sex-disaggregated outcome data were reported, they were rarely analysed as a primary stratification variable, and none of included studies formally examined whether sex or gender modified susceptibility to HRI, response to adaptation interventions or access to on-site care. Consequently, the synthesized findings should be interpreted as reflecting a predominantly male and, in religious mass gathering contexts, older population with multiple comorbidities, with limited ability to inform sex- and gender-responsive event planning. Furthermore, the methodological quality of the underlying literature constitutes a notable limitation; 56% of the included studies demonstrated a moderate to serious risk of bias, largely attributable to unmeasured confounding and selection bias, as outcome data were exclusively captured from attendees who actively sought medical care, thus potentially underestimating the true community burden of heat strain.

Additionally, many of the operational data regarding event planning, costs and feasibility are likely to be held in unpublished post-event technical reports or internal government documents

(grey literature), which were excluded from this review to maintain methodological rigour. Consequently, our findings regarding the financial costs and logistic feasibility of adaptation measures are likely to be understated.

Although a small number of included studies, such as descriptive epidemiological case series, did not perfectly align with the selected risk-of-bias tool (ROBINS-I), the tool was considered sufficiently appropriate for the predominant study designs included in the review and allowed a consistent and transparent appraisal across studies. Current methodological guidance emphasizes justification and consistent application of risk-of-bias assessment tools, rather than adopting multiple tools depending on individual study design (110).

Finally, the denominator data (exact crowd sizes) were frequently estimated or absent in the primary studies, making it difficult to calculate true incidence rates for HRIs across different events. Future research should prioritize standardized reporting frameworks for mass gathering medicine (such as the Minimum Data Set proposed by the WHO collaborating centres) (111). This would emphasize precise denominator tracking, sex- and gender-disaggregated outcome reporting, time-stratified analyses that reflect the evolution of heat-management practice, rigorous cost-benefit analyses of cooling interventions and qualitative research into the behavioural drivers of heat-risk in crowds.



Run and Ride Event - Pakistan - 27 April 2025. © WHO

Systematic review 2

Integrated early warning, crowd/capacity management, mobile apps and dynamic heat sensing

2.1 Introduction

As established in the broader context of mass gatherings, the convergence of extreme environmental heat exposure, high crowd density and vulnerabilities due to diverse demographic characteristics creates a profound “risk signature” that frequently overwhelms local public health capacities. While traditional, static heat adaptation strategies, such as the provision of cool rest zones, misting fans and hydration stations, remain foundational to event planning, their efficacy is inherently limited by their reactive nature. These structural interventions rely heavily on attendee compliance and often fail to adapt to the rapidly fluctuating dynamics of crowd movement, localized microclimates and sudden surges in physiological strain (**SR1**). As climate change accelerates the frequency and intensity of extreme heat events, there is an urgent requirement to transition from reactive medical management to proactive, data-driven heat-risk anticipation.

In recent years, the rapid evolution of digital health ecosystems, driven by advances in AI, the IoMT and real-time data infrastructures, has presented novel opportunities for mass gathering health management (20, 112). Early warning and response systems have increasingly incorporated dynamic heat-sensing technologies, syndromic surveillance dashboards and personalized mobile health applications. At the individual level, wearable biosensors paired with AI algorithms can continuously acquire physiological data, such as heart rate variability, skin temperature and electrodermal activity, to detect the earliest autonomic signs of heat exhaustion before clinical collapse occurs (113-115). At the macro-operational level, large-scale predictive models and digital surveillance platforms integrate historical incident data with real-time patient analytics and dynamic weather indicators to forecast emergency patient volumes and optimize the spatial redeployment of medical resources (116, 117).

Despite the proliferation of these digital health tools, their translation from isolated technological innovations into scalable, operational public health systems remains highly fragmented (118, 119). The mass gathering environment presents extreme logistic and technical hurdles (2, 120), including overwhelmed mobile phone networks, differences in user acceptability driven by cultural or privacy concerns (121), and the limitations of consumer-grade sensors under intense physical exertion. Furthermore, current predictive models rely too heavily on static meteorological data (e.g. ambient temperature) while failing to account for the dynamic, unmeasured complexities of crowd behaviour and demographic risk factors (122). Modern frameworks increasingly recognize that technological interventions are most effective when they function as integrated, end-to-end cyber-physical systems, where environmental sensing

and physiological monitoring are directly linked to automated alerts and predefined operational crowd-management protocols (123).

WHO and global health security agencies increasingly emphasize the need for robust, evidence-based integration of digital early warning systems into public health emergency preparedness (124). Yet, a critical gap remains in evaluating whether these advanced surveillance and sensing platforms actually translate into measurable reductions in heat-related morbidity and mortality during major events. Therefore, this systematic review aimed to evaluate the clinical effectiveness, operational timeliness, implementation feasibility and user acceptability of integrated heat early-warning and real-time heat-risk management systems during mass gatherings, thus providing critical insights into the current capabilities and limitations of digital health technologies in high-density, extreme-heat environments.

2.2 Methods

2.2.1 Study design and reporting framework

This systematic review was designed and conducted in accordance with the PRISMA 2020 statement (35). The methodological approach followed the same framework and procedures as described for **SR1.2.1**. This included the use of a predefined protocol structured around a PICO framework to ensure transparency, reproducibility and conceptual clarity. All methodological steps, including protocol development, study selection and data extraction, were consistent with those described in **SR1.2.1**. The study protocol was registered in the OSF and can be accessed via the registration identifier (<https://osf.io/7xa95/>).

2.2.2 Review question

The review addressed the following question in PICO format: Among spectators, volunteers, staff, security and other workers, and local communities affected by major mass gathering events in hot or chronically hot environments (P), does exposure to integrated heat early-warning and real-time heat-risk management systems (linked to crowd management, ticketing/registration systems, mobile applications and dynamic heat sensing/mapping) (I), compared with less- or non-integrated or minimal heat systems (C), reduce HRI and unsafe crowd conditions (O)? The full PICO framework, including population stratification, intervention typologies and outcome domains, is provided in Annex 1.2.

2.2.3 Eligibility criteria

Studies were considered eligible if they met all predefined inclusion criteria. Eligible populations included attendees, spectators, volunteers, security personnel, staff and other workers involved in major outdoor or semi-outdoor mass gathering events in hot or chronically hot environments. Events included major sporting events as well as large religious, cultural, political or festival gatherings. Studies conducted outside mass gathering contexts were excluded.

Eligible interventions comprised integrated heat stress risk-management systems that relied on empirically collected local data and linked heat early-warning thresholds to operational decision-

making. These included systems integrating heat alerts with crowd or flow management, logistics and capacity controls, ticketing or registration platforms, mobile applications providing real-time advisories, dynamic heat sensing or mapping technologies, and predefined crowd-sensitive response protocols. Systems based solely on static meteorological information without operational integration were excluded.

Comparators included mass gatherings without heat-specific early-warning systems, systems with minimal or non-integrated heat information, or pre-implementation periods in before–after studies.

Eligible outcomes included heat-related health events such as on-site presentations of HRI, number of cases treated, hospitalizations, intensive care admissions and deaths. Crowd-safety incidents occurring under hot conditions, including fainting clusters, uncontrolled crowd movement or heat-triggered mass incidents, were also eligible. Secondary outcomes of interest included timeliness and appropriateness of operational responses, feasibility of implementation, costs, user acceptability and equity considerations.

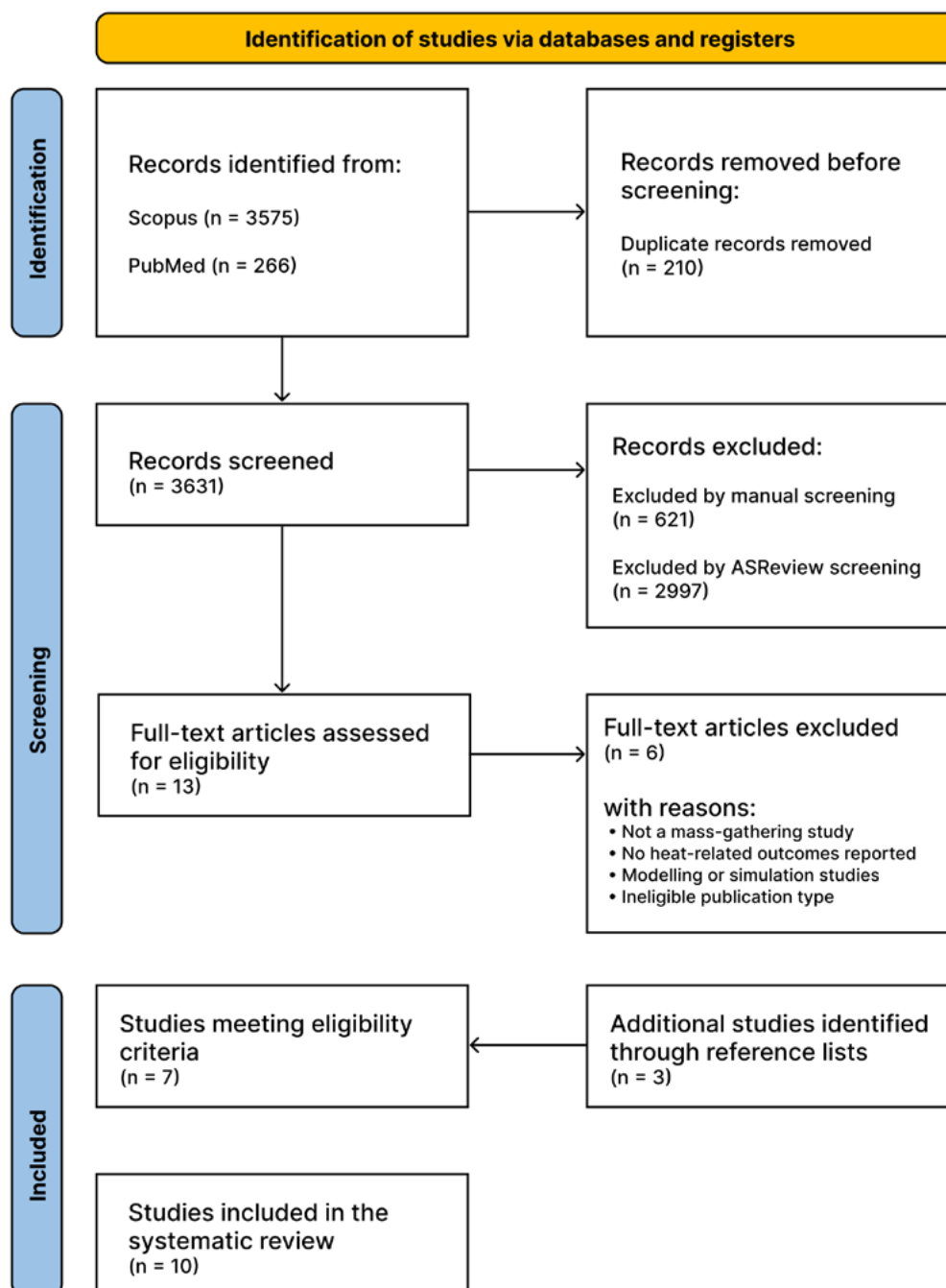
Only original empirical studies using quantitative, qualitative, modelling or mixed-methods designs were eligible. Given the technological nature of the intervention, studies developing, validating or evaluating prediction models were included. Reviews, systematic reviews, meta-analyses, editorials, commentaries, letters to the editor, conference proceedings without full papers, books and book chapters were excluded. Publications for which full text could not be retrieved after reasonable efforts were also excluded.

2.2.4 Information sources and search strategy

The literature search was conducted using the same databases, search strategy development process and execution procedures as described in **SR1.2.3**. Search terms were adapted to reflect the specific intervention domain of integrated early-warning and real-time heat-risk management systems. The final searches were conducted on 16 January 2026, and the full search strategies are reported in Annex 2.2.

2.2.5 Study selection and screening

The study selection and screening process, including the use of ASReview for title and abstract screening (36, 37), independent screening by two reviewers (MV; KM), resolution of discrepancies and application of a stopping rule, mirrored the procedures detailed in **SR1.2.4**. Reasons for exclusion at the full-text stage were recorded systematically and are reported in the PRISMA flow diagram (Fig. 3). Backward reference searching was also performed for all included full-text articles.

Fig. 3. PRISMA flow diagram of the study selection process of SR2^a

^a The flow chart details the systematic methodology for identifying, screening and selecting eligible studies for inclusion in the review.

2.2.6 Data extraction

Data extraction was performed independently by two reviewers (KM; MP) using a predefined and pilot-tested data extraction form, consistent with **SR1.2.5**. Extracted variables included authorship, year of publication, country and setting of the event, study design, characteristics of the mass gathering, environmental heat conditions, description of the integrated system architecture, data sources and predictors used, validation status of prediction models, operational integration components, reported health and crowd-safety outcomes, and secondary outcomes related to feasibility, costs, equity and user acceptability. Discrepancies were resolved through discussion or by a third reviewer (ADF). The complete data extraction table is provided in Annex 3.3.

2.2.7 Risk of bias assessment

Risk of bias was assessed using the PROBAST (Prediction model Risk of Bias Assessment Tool) (125), which is specifically designed for studies developing, validating or evaluating diagnostic and prognostic prediction models and evaluates both risk of bias and concerns regarding applicability. The tool assesses risk of bias across four domains: participants, predictors, outcome and analysis.

- The Participants domain evaluates representativeness of the study population.
- The Predictors domain examines clarity and measurement of model inputs and their availability at the time of intended use.
- The *Outcome* domain assesses the definition and measurement of heat-related or crowd-safety outcomes.
- The Analysis domain evaluates model development procedures, handling of missing data, predictor selection, overfitting, validation processes, calibration and reporting transparency.

In addition to risk of bias, PROBAST assesses concerns regarding applicability across the domains of participants, predictors and outcome. Applicability judgements examined whether study populations reflected major mass gathering settings in hot environments, whether predictors were feasible for real-time operational implementation, and whether outcomes were aligned with clinically and operationally relevant heat-risk events.

Each domain was judged as having a low, high or unclear risk of bias, and concerns regarding applicability were rated as low, high or unclear. Two reviewers (AC; GG) independently conducted the assessment. Discrepancies were resolved through discussion and, where necessary, adjudication by a third reviewer (ADF). Risk of bias and applicability assessments were used to inform interpretation of findings but were not used as exclusion criteria.

2.2.8 *Data synthesis*

Due to the pronounced methodological and technological heterogeneity of the included studies, which encompassed wearable physiological sensors, machine-learning classification models, pre-event regression-based predictive models, multi-objective mathematical optimization and real-time syndromic surveillance platforms, a quantitative meta-analytical approach was not feasible. A structured narrative synthesis was therefore undertaken, guided by the SWiM reporting framework (41).

Extracted data (Annex 3.3) were organized in a thematic matrix and studies were grouped according to three prespecified intervention domains reflecting the PICO framework:

1. individual-level wearable sensors and machine-learning applications;
2. pre-event predictive modelling and operational planning tools; and
3. real-time integrated digital surveillance and early warning systems.

Within each domain, synthesis addressed system architecture and data inputs, validation approach, reported model performance metrics (e.g. accuracy, sensitivity, specificity and area under the curve where available), linkage to operational response protocols, and any downstream clinical or crowd-safety outcomes. Cumulative descriptive counts, including the total number of attendees covered, participants enrolled in validation cohorts, clinical encounters captured and HRI detected, were aggregated across studies where denominators were explicitly reported.

Secondary outcomes of timeliness, feasibility, user acceptability and equity were synthesized narratively across all three domains to identify cross-cutting implementation barriers and enablers. The PROBAST judgements on both risk of bias and applicability concerns were integrated into the synthesis, so that conclusions regarding the real-world transferability of each technology were weighted against the representativeness of the validation populations and the methodological rigour of model development. Given the predominantly pilot or proof-of-concept nature of the evidence, no attempt was made to pool performance metrics quantitatively; instead, patterns and divergences across studies were described and interpreted.

2.3 Results

A total of 3841 records were identified through our systematic search. The articles were written in 24 languages: 3617 in English, 121 in Chinese, 20 in Spanish, 18 in German, 17 in Russian and 10 in French. The remaining 38 articles (1% of total) were written in other languages. Following the removal of 210 duplicate records, 3631 records were screened, of which 3618 were excluded after title/abstract screening (621 manually and 2997 via ASReview). This resulted in 13 eligible reports sought for retrieval. Of the 13 full-text articles assessed for eligibility, 6 were excluded for various reasons including: no heat-related outcomes, modelling or simulation studies, not being a mass-gathering study, or being an ineligible publication type such as a review, letter or editorial. Consequently, seven studies met the initial eligibility criteria. Three additional studies were identified through the screening of reference lists, yielding a final total of 10 studies included in the systematic review.

Of the 10 included studies, 4 (40%) provided no information regarding their funding source or funding type. The remaining 6 (60%) studies reported an active funding source. All of these supported studies were classified under government, university or charitable funding types, including grants from ministries of education, university entrepreneurship centres, and ambulance or hospital research funds.

The studies included in the analysis were published between 1992 and 2025. The research utilized a diverse mix of methodologies, including observational study designs, cross-sectional studies, and applied system/technology development. All included studies were published in English. The studies were conducted across six countries (Australia, Iraq, Saudi Arabia, Trinidad and Tobago, United Arab Emirates and the United States of America). They included information on three broad categories of mass gathering events: religious pilgrimages, sporting competitions, and a combination of other events including fairs and outdoor concerts. The mass gatherings analysed, which prominently featured the Hajj pilgrimage, the International Cricket Council (ICC) Men's T20 Cricket World Cup and the Indianapolis 500, took place between 1983 and 2024. Event durations ranged from a single day to multi-week tournaments with some studies reporting aggregated year-long operational data. The main characteristics and technological outcomes of these mass gatherings are reported in Annex 3.3.

The mass gatherings investigated in the studies analysed had a total estimated attendance of more than 15 million individuals. The study populations analysed in the included articles were predominantly composed of religious pilgrims ($n=7$; 70% of articles) and event spectators ($n=3$; 30% of articles). Additional groups assessed encompassed general visitors and the event staff or paramedics utilizing the technological systems. The cumulative attending population across all the mass gatherings analysed was very large. However, the specific study populations, comprising individuals who sought on-site medical care, participated in real-world wearable sensor trials or were captured by digital syndromic surveillance platforms, amounted to approximately 14 000 recorded individuals. It is important to note that the vast majority of patients (nearly 12 000) seen during these encounters were recorded in a single large-scale predictive modelling study analysing patient presentations across Australian mass gatherings (126). By contrast, the remaining nine studies investigated smaller, highly targeted cohorts (ranging from 2 to 1200 participants), designed to test specific wearable, AI or surveillance technologies.

2.3.1 *Demographic characteristics*

The demographic characteristics of the studied populations varied significantly depending on the nature of the study design and the cultural context of the event. For instance, large-scale observational and surveillance studies capturing real-world event dynamics (126-129) frequently reported highly diverse patient cohorts. As reported in the broader literature on mass gatherings, clinical surveillance at religious mass gatherings such as the Hajj (129) generally involved older populations, with a mean age of 47 years and a slightly higher proportion of male attendees (56.3%). Consequently, these older cohorts demonstrated a notable prevalence of underlying pre-existing comorbidities. Baseline tracking in these groups revealed rates of hypertension (16.5%), diabetes mellitus (7.8%) and asthma (4.8%), which directly exacerbated their vulnerability to severe HRI. Furthermore, this event demonstrated a highly multinational participant pool, drawing study participants of diverse ethnicities (55.0% Arab, 29.4% Asian, and 6.5% African), with the vast majority (76.2%) travelling from outside the host country. Validation studies and those on wearable technology (130-132) utilized highly controlled, homogeneous and much younger micro-cohorts. For example, baseline tracking in these technology-focused groups revealed cohorts consisting entirely of university students with a narrow age range of 20 to 27 years (mean: 21.9 years), and 100% male participants (131), or exceedingly small test groups of just two or three individuals (130, 132). However, since the included studies focused on the deployment and validation of wearable physiological sensors, they did not all provide age, sex or comorbidity stratification for their patient datasets.

2.3.2 *Health outcomes*

The reporting of explicit health outcomes across the 10 included studies was heavily dependent on the type of technological intervention being evaluated. Studies implementing broad digital surveillance systems and predictive modelling successfully captured massive datasets of patient encounters, whereas studies focusing on the pilot validation of specific machine-learning or wearable technologies often did not report downstream clinical outcomes, focusing instead on the technical accuracy of the devices.

In total, the included studies recorded more than 13 000 clinical encounters across the mass gatherings evaluated (Annex 3.3). As seen in SR1, the clinical burden observed at sporting and secular mass gatherings was heavily dominated by non-heat-related presentations, particularly minor trauma and general medical issues. For example, the predictive modelling of Australian mass gatherings (126) recorded a total of 11 956 patient presentations, of which 3084 were for minor injuries, while HRI accounted for only 126 cases. Similarly, digital syndromic surveillance deployed during the Cricket World Cup (128) identified a total of 146 cases of ill health, which included 33 patients with traumatic injuries, 17 syndromic infectious disease alerts and 22 specific mentions of HRI.

It is important to note that because these massive, aggregated datasets frequently span from the late 1990s to the early 2000s, they encompass the global transition from the ICD (International Classification of Diseases)-9 to the ICD-10 diagnostic coding systems. Consequently, potential coding variations and reclassifications of specific environmental exposures before and after 1999 may introduce minor inconsistencies in how historical HRI were aggregated in these longitudinal models (133).

Clinical studies reported in the evaluated literature focused on religious pilgrimages in desert climates, highlighting the acute severity of heat strain. A detailed diagnostic study of Hajj pilgrims (129) identified 231 with confirmed or suspected HRI among 1200 individuals encountered. This included 14 explicitly diagnosed cases of heatstroke and 40 cases of heat exhaustion. The most frequently reported symptoms among heatstroke patients were dizziness (86%), fatigability (64%) and headache (43%). Another operational study at the Hajj (134) recorded 713 emergency department presentations, differentiating them into 465 non-critical cases and 248 critical cases requiring surgery or intensive care, although it did not explicitly report the number of heat-induced presentations among the cases characterized as critical.

2.3.3 Technological strategies and early warning systems

The technological interventions evaluated across the 10 included studies encompassed a broad spectrum of digital health and surveillance innovations. These strategies can be broadly categorized into three main domains: individual-level wearable sensors and machine-learning applications (n=6; 60%), pre-event predictive modelling and operational planning tools (n=3; 30%), and real-time integrated digital surveillance and early warning systems (n=1; 10%).

Most of the included studies (60%) focused on the development and pilot testing of individualized monitoring technologies, exclusively within the context of the Hajj pilgrimage. To capture continuous physiological data in a highly mobile and dense crowd, investigators deployed multimodal wearable systems. Two studies (130, 131) utilized a combination of wristbands and chest-worn sensors synced to custom mobile applications to track heart rate, skin temperature, electrodermal activity and respiration rate. Another pilot study (132) utilized consumer-grade smart watches paired with smartphones to continuously monitor heart rate variability and physical exertion, based on participant feedback and observed performance metrics. The data generated from these wearables and mobile applications were frequently integrated with advanced machine learning algorithms. Studies utilized deep learning (131) and decision tree ensembles (129) to classify pilgrim activity types, predict physical fatigue and stratify the risk of HRIs based on electronic surveys. Beyond physiological monitoring, machine-learning was leveraged to overcome mass gathering-related logistic barriers. Albalawi et al. (2025) (135) developed a machine-learning-driven facial recognition application to allow paramedics rapid access to patient medical histories, while Alghamdi & Mostafa (2024) (136) engineered a multilingual large language model chatbot utilizing retrieval-augmented generation to provide reliable, culturally sensitive health and heat-risk guidance directly to pilgrims.

Only one study, by Daniel et al. (2025) (128), explicitly detailed the implementation of a comprehensive, real-time early warning and response system linked to operational crowd management in the Caribbean Region. Deployed during the 2024 Cricket World Cup across six Caribbean countries, this system utilized an electronic mass gathering surveillance module built on the Tourism and Health Information System platform. The technology enabled real-time digital data entry via tablets at stadiums and fan zones, utilizing predefined syndromic thresholds (including HRI, trauma and acute gastroenteritis). Crucially, this system featured an automated early warning mechanism. When case thresholds were exceeded, automated email alerts were immediately dispatched to on-site surveillance teams and Ministry of Health officials. This real-time detection directly triggered operational public health actions, such as the rapid deployment of additional cooling and hydration areas ahead of final matches.

The remaining 30% of studies focused on pre-event predictive modelling to optimize medical resource allocation rather than real-time monitoring. Two studies (126, 127) utilized empirical meteorological data to build regression models aimed at predicting daily emergency patient volumes and hospital transport rates based on variables such as ambient temperature, relative humidity and dew point. While a large Australian study (126) found that environmental factors combined with crowd size and event type accounted for up to 64% of the variance in patient presentations, a study on motor racing events in the United States of America (127) found that while dew point correlated strongly with patient load retrospectively, the model failed external validation in subsequent years. This highlights the limitations of relying solely on simple weather metrics without dynamic crowd data. Finally, one operational research study (134) utilized a multi-objective mathematical optimization model to simulate and optimize ambulance fleet sizes and spatial redeployment strategies across the Hajj site, ensuring 95% geographical coverage during peak demand hours.

2.3.4 Timeliness, feasibility and user acceptability

The timeliness of operational responses was a prominent strength highlighted in studies evaluating real-time systems. Across the reviewed literature, integrated early warning mechanisms and automated threshold alerts facilitated rapid notification loops between field teams and health authorities. This immediacy enabled rapid on-site verification and directly triggered pre-emptive public health actions, such as the proactive deployment of targeted cooling and hydration resources to prevent the escalation of HRI (128). Similarly, localized, individual-level technologies significantly improved clinical response times. Mobile applications granting rapid access to patient medical histories, and wearable sensors featuring automated alerts for physiological anomalies were explicitly shown to reduce emergency response delays and enable proactive medical interventions before severe physiological collapse occurred (132, 135).

Implementation feasibility, while frequently challenged by the extreme logistic and physical environments of mass gatherings, demonstrated notable success across a range of scales. Regional digital surveillance platforms proved highly scalable, achieving consistent real-time data entry and reporting across sites with multinational attendees (128). For individual-level wearable technologies, maintaining device power and continuous data connectivity in dense, highly mobile crowds emerged as the primary feasibility hurdles. Nevertheless, studies that strategically adapted their data collection protocols to the specific logistic flow of the event achieved exceptionally high data continuity rates (132). Conversely, approaches relying solely on predictive modelling using publicly available meteorological data, while highly feasible in terms of initial data acquisition, were ultimately deemed to have limited practical applicability in real-world settings. These models often failed to accurately forecast emergency patient volumes, highlighting the inadequacy of static weather data when divorced from the dynamic, unmeasured complexities of crowd behaviour (127).

Across the included literature, user acceptability was consistently found to be closely intertwined with ease of use, stringent data privacy and cultural sensitivity. For large-scale digital surveillance systems, acceptability was primarily driven by institutional engagement. Ministry of health leadership, early stakeholder (surveillance doctors and nurses) training and user-friendly, tablet-based, reporting interfaces resulted in high adoption rates among field staff and participating health ministries (128). Conversely, for individual-level interventions involving AI,

tracking technologies or biometric data, ensuring cultural acceptability and ethical deployment was paramount. Multiple studies emphasized “privacy-by-design” architectures to foster user trust, employing secure authentication to restrict access to medical data, strict anonymization protocols and culturally sensitive informed consent processes (132, 135). Furthermore, the successful deployment of automated health stress risk communication tools depended on their ability to recognize and respect the cultural nuances and multinational backgrounds of the attendees, ensuring that digital guidance was not only medically accurate but also equitable and contextually appropriate (136).

2.3.5 Risk of bias and applicability assessment

The methodological quality and practical relevance of the 10 included studies were evaluated using the PROBAST tool, which assesses both the risk of bias and concerns regarding applicability for diagnostic and prognostic prediction models. Overall, the methodological quality of the included studies was mixed, with 60% being judged to have an overall low risk of bias, while the remaining 40% demonstrated a high risk (Fig. 4a). The evaluation across specific domains revealed that the measurement and blinding of the technological inputs (the Predictors domain) demonstrated the highest rigour, with 100% of studies rated as low risk. The Outcome domain also performed strongly, with 90% of studies maintaining a low risk of bias regarding how heat-related or crowd-safety events were defined and measured. The primary drivers of elevated bias stemmed from the Analysis and Participants domains, each of which had 30% of studies rated at high risk. The high risk within the Analysis domain highlights methodological shortcomings in specific studies, such as inadequate sample sizes for model training, a lack of external validation or insufficient handling of missing data. Similarly, the high risk in the Participants domain reflects issues with selective or non-representative sampling, a common limitation in pilot studies deploying novel wearable sensors in small, homogeneous cohorts.

Regarding the applicability of the models and technologies tested to real-world mass gathering settings, overall concerns mirrored the risk of bias. Specifically, 60% of studies were judged as having low applicability concerns, while 40% raised high concerns (Figure 4b). Notably, concerns regarding the practical relevance of the Predictors and the clinical relevance of the Outcomes were universally low (100% low concern across both domains). This indicates that the technological metrics (e.g. continuous physiological monitoring, meteorological data) and the targeted end-points (e.g. predicting fatigue, HRI triage) are highly appropriate for mass gathering environments. The 40% overall high concern was entirely driven by the Participants domain, where 30% of studies raised high concerns. This reflects the demographic disconnect noted earlier. Many technological pilot interventions utilized highly controlled, unrepresentative micro-cohorts (e.g. young, healthy, exclusively male university students (131) whose physiological responses and behaviours may not be applicable to the broader, high-risk population groups that characterize major events such as the Hajj.

2.4 Discussion

This systematic review synthesized evidence from 10 studies of mass gatherings with a cumulative attendance exceeding 15 million individuals over a period of 41 years, to evaluate the effectiveness of integrated early warning systems, mobile applications and dynamic heat-sensing technologies. The findings highlight a rapidly evolving digital health ecosystem, increasingly driven by advances in AI, the IoMT and real-time data infrastructures. The integration of real-time surveillance with operational crowd management demonstrates substantial potential for mitigating heat-related risks. However, studies on most of the emerging technologies, particularly AI-enabled wearables and predictive analytics platforms, remain confined to the pilot or proof-of-concept stages, underscoring a persistent gap between technological capability and scalable public health deployment (130-132). This reflects a broader trend in digital health, where wearable biosensors and AI systems are technically mature but not yet widely embedded into population-level health systems (137). Notably, despite the large scale of events and high clinical workload reported, none of the included studies documented mortality attributable to heat exposure during periods when technological interventions were active.

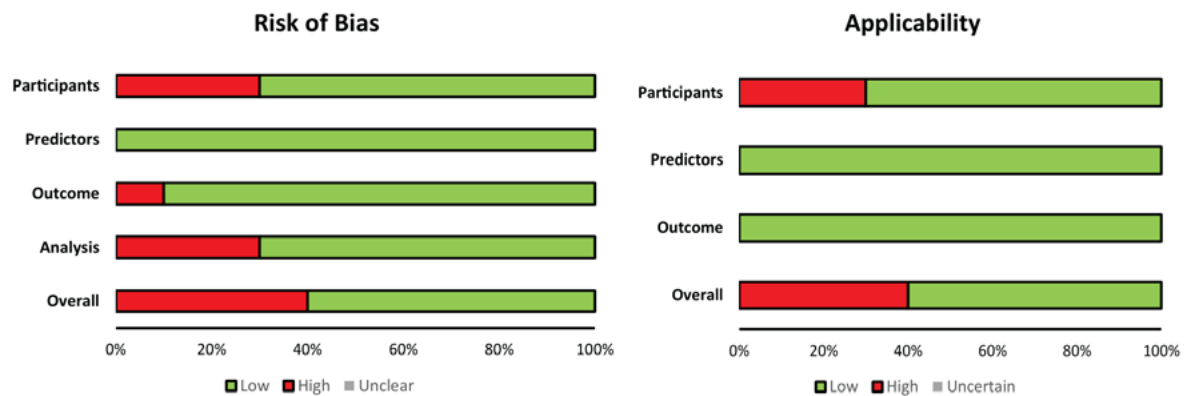
Fig. 4. Risk of bias assessment of the 10 included studies using the PROBAST tool (a) and summary of judgements across specific bias domains and applicability (b)

(a)

	Risk of bias					
	Participants	Predictors	Outcome	Analysis	Overall risk of bias	
Alkassas 2020	+	+	+	+	+	Low risk
Naji 2024	+	+	+	+	+	Low risk
Al-Shaery 2024	X	+	+	+	X	High risk
Al-Shaery 2022	X	+	X	X	X	High risk
Albalawi 2025	+	+	+	+	+	Low risk
Alshamrani 2025	X	+	+	X	X	High risk
Alghamdi 2024	+	+	+	+	+	Low risk
Daniel 2025	+	+	+	+	+	Low risk
Arbon 2001	+	+	+	+	+	Low risk
Bowdish 1992	+	+	+	X	X	High risk

	Applicability				
	Participants	Predictors	Outcome	Overall applicability	
Alkassas 2020	+	+	+	+	Low concern
Naji 2024	+	+	+	+	Low concern
Al-Shaery 2024	+	+	+	+	Low concern
Al-Shaery 2022	X	+	+	X	High concern
Albalawi 2025	+	+	+	+	Low concern
Alshamrani 2025	X	+	+	X	High concern
Alghamdi 2024	+	+	+	+	Low concern
Daniel 2025	X	+	+	X	High concern
Arbon 2001	+	+	+	+	Low concern
Bowdish 1992	+	+	+	+	Low concern

(b)



A central finding is the clear technological and methodological divide between macro-level digital surveillance systems and micro-level wearable technologies. Large-scale platforms, such as syndromic surveillance systems and epidemic intelligence tools (138), have demonstrated strong capability for early signal detection, enabling rapid decision-making and coordinated response across health systems (139). These systems leverage multisource data streams, including clinical reports, environmental data and open-source intelligence, to generate actionable alerts in a near real-time situation. In contrast, most of the studies reviewed (60%) focused on wearable physiological monitoring technologies and mobile health applications, particularly within the Hajj context. These systems rely on continuous bio-signal acquisition (e.g. heart rate, skin temperature, electrodermal activity), which can be processed using AI and machine learning algorithms to enable personalized, predictive health monitoring (140). While these technologies demonstrate high analytical accuracy, often exceeding 90% in controlled validation settings, they function primarily as individual-level diagnostic or monitoring tools rather than integrated, population-level early warning systems (141).

Modern wearable systems are increasingly conceptualized as end-to-end cyber-physical systems, combining sensors, cloud connectivity, and AI-driven analytics capable of generating automated alerts and recommendations (142, 143). However, their current deployment in mass gatherings remains largely fragmented (144). Even advanced AI-enabled wearables, which can detect physiological anomalies and predict health deterioration hours in advance, are typically evaluated in small, homogeneous cohorts and are not integrated with operational command systems that govern crowd safety (130). Furthermore, as highlighted in stakeholder-based research from deployments during the Hajj, barriers to implementation include infrastructure limitations, device usability, cost and organizational integration challenges (145).

Importantly, AI-driven systems are beginning to transform the broader paradigm of health management at mass gatherings. Recent evidence suggests that AI-based predictive analytics can synthesize environmental, demographic and behavioural data to forecast health risks, optimize resource allocation and support real-time decision-making during large events (146). Similarly, task-force-based evaluations of AI deployment during the Hajj, including automated early detection and response systems, emphasize its role in triage, predictive modelling, virtual care and operational efficiency (147). However, very few studies demonstrated this critical “closed-loop” integration. The most effective systems were those that combined real-time surveillance

with predefined response protocols, enabling immediate operational action following threshold exceedance. This aligns with the concept of intelligent sensing platforms, where data acquisition, processing and decision-making occur continuously and autonomously, supported by AI-driven analytics (148). In contrast, studies relying on static or pre-event predictive models, particularly those based solely on meteorological inputs, consistently underperformed during real-world validation. This reinforces the growing consensus that effective prediction of heat stress risk requires multimodal data fusion, integrating environmental, physiological and behavioural inputs within dynamic, real-time frameworks.

From an implementation perspective, technological feasibility alone is insufficient. The effectiveness of digital health systems during mass gatherings depends strongly on interoperability, scalability and user acceptance. Wearable and mobile technologies face persistent challenges related to battery life, network connectivity and data reliability in high-density environments (149). At the same time, the ethical and sociocultural dimensions of technology deployment are increasingly recognized as critical determinants of success. Privacy-preserving architectures, secure data governance and culturally adapted communication interfaces are essential for fostering trust and adoption, particularly in sensitive contexts such as religious mass gatherings (150). These considerations are consistent with WHO digital health principles emphasizing equity, inclusivity and user-centred design.

Ultimately, this review demonstrates that, while the technological building blocks for advanced heat stress risk management, AI, wearable biosensors, IoMT platforms and real-time surveillance systems, are already available, their integration into cohesive, scalable public health systems remains incomplete. The current evidence base is dominated by technical validation studies rather than outcome-driven evaluations. Future research must prioritize large-scale, real-world trials of fully integrated systems that combine environmental sensing, physiological monitoring and operational response, and that explicitly measure clinical outcomes, system performance and crowd-safety indicators. Bridging this gap will require interdisciplinary collaboration between engineers, data scientists, public health experts and policy-makers to ensure that technological innovation translates into measurable health protection at scale.

2.5 Limitations

This systematic review is subject to several limitations, largely reflecting the nascent state of the evidence base concerning digital health technologies for mass gatherings. A key limitation of this review is the relatively small number of eligible studies, which limits the robustness of the conclusions and highlights the need for further research in this area. The methodological quality of the included literature is another important limitation. According to the PROBAST assessment, 40% of the included studies demonstrated an overall high risk of bias, heavily driven by critical flaws in the Analysis domain. Predictive models and machine learning algorithms were frequently developed using inadequate sample sizes, lacked external validation across independent mass gathering events and demonstrated insufficient handling of model overfitting (126, 127). Consequently, the statistical reliability of many of these pilot technologies remains questionable in terms of their suitability for large-scale, operational deployment.

Moreover, the review identified significant demographic and geographical skew in the available data. Most (60%) of the technological pilot interventions, particularly those validating wearable sensors and mobile applications, were conducted exclusively during the Hajj pilgrimage where participants were more likely to be male than female (129-132, 135, 136). Furthermore, these validation studies frequently utilized highly controlled, homogeneous micro-cohorts, such as exceedingly small test groups or groups consisting entirely of young, healthy, male university students (130-132). This demographic disconnect limits the generalizability of the findings, as the physiological responses of these test subjects do not accurately reflect the vulnerability of older adults with pre-existing comorbidities, who represent the primary at-risk population for severe heat-related morbidity at such events.

There is a distinct lack of robust epidemiological evidence linking the deployment of these technologies to hard clinical end-points. While the studies frequently reported on technical accuracy (e.g. algorithm precision or sensor continuity), none of the 10 included studies explicitly measured the impact of integrated early warning systems or wearables on reducing the true incidence of severe heatstroke, hospitalizations or heat-related mortality over time (126-132, 134-136). The focus of the current literature remains overwhelmingly on technical validation rather than long-term clinical or public health outcomes.

Finally, the review's reliance on peer-reviewed literature may have resulted in the omission of critical operational data regarding the real-world deployment, cost-effectiveness and logistic failures of event-based surveillance systems (128) or proprietary crowd-management software. Such information is often contained in unpublished post-event technical reports or private organizational documents (grey literature). Consequently, the true financial costs of and feasibility barriers to implementing these digital health systems are likely to be understated.



74th session of the WHO Regional Committee for Africa, Brazzaville, Republic of the Congo, 26-30 August 2024. © WHO

Systematic review 3

Visitor knowledge, behaviour, vulnerability identification and wearable alerts

3.1 Introduction

While structural heat adaptation (as explored in **SR1**) and macro-level digital surveillance platforms (**SR2**) are foundational to mass gathering safety, these approaches often treat the crowd as a uniform entity. In reality, the burden of environmental heat stress is profoundly inequitable. Heat-related morbidity and mortality at mass gatherings disproportionately affect specific, highly vulnerable subgroups. Older adults, children, pregnant individuals and people with pre-existing chronic conditions (such as cardiovascular disease, diabetes, renal diseases and hypertension) face severe physiological disadvantages, including impaired thermoregulation and altered thirst perception (7, 151). Furthermore, culturally and linguistically diverse communities, and international visitors unacclimatized to extreme local temperatures are particularly susceptible to rapid heat exhaustion, a risk frequently compounded by language barriers that render generic emergency broadcasting ineffective (33, 152, 153).

Protecting these high-risk populations requires a transition towards “precision mass gathering preventive medicine”. Standard, one-size-fits-all risk communication, such as generic public address announcements or basic digital signage, often fails to catalyse actual protective behaviours (154). As observed in diverse mass gathering settings, particularly during religious pilgrimages like the Hajj, attendees frequently exhibit a profound “knowledge–action gap”. Even when individuals are acutely aware of the extreme heat, psychological factors, cognitive overload or deep-rooted spiritual and cultural imperatives often drive them to override their own physical limits, leading them to bypass cool zones or refuse necessary medical interventions (12, 155). Therefore, risk communication cannot merely be informational; it must be culturally resonant, linguistically tailored and behaviourally actionable. To overcome these behavioural barriers, proactive engagement is critical. Modern public health frameworks advocate for the implementation of pre-event vulnerability identification mechanisms, such as pre-registration health screening or special ticketing categories, that allow event organizers to pinpoint at-risk individuals before they step into the heat (21, 156). When coupled with tailored, multichannel communication and personalized wearable alert tools designed to detect physiological strain and prompt immediate protective action, these targeted interventions have the potential to intercept the progression of HRI before it necessitates an emergency clinical response (157–159). WHO has increasingly emphasized that health interventions in crowded, climate-stressed environments must be equitable and inclusive (160). Yet, it remains unclear how effectively global event organizers are identifying and prioritizing the vulnerable groups in practice. Therefore, this systematic review aimed to evaluate the implementation and effectiveness of tailored heat-stress risk communication, proactive vulnerability identification mechanisms and

personalized wearable alert tools. By assessing their impact on improving protective behaviours and reducing HRI among high-risk subgroups, this review sought to provide actionable evidence on safeguarding the most vulnerable attendees in an increasingly warming world.

3.2 Methods

3.2.1 Study design and reporting framework

This systematic review was designed and conducted in accordance with the PRISMA 2020 statement (35), consistent with the approach outlined in **SR1.2.1**. All methodological steps, including protocol development, study selection, data extraction and risk of bias assessment, were conducted consistently with those described in **SR1.2.1**. The study protocol was registered on the OSF and can be accessed via the registration identifier (<https://osf.io/23cwu/>).

3.2.2 Review question

The review addressed the following question in PICO format: Among participants and staff (older adults, children, pregnant people, individuals with chronic disease or disability, culturally and linguistically diverse community members and heat-unacclimatized visitors) of mass gathering events in hot or chronically hot environments (P), does exposure to tailored heat stress risk communication, vulnerability identification and wearable alert tools (I), compared with standard or generic approaches or no such tools (C), improve protective behaviours and reduce HRI, especially among vulnerable groups (O)? The full PICO framework, including population stratification, intervention typologies and outcome domains, is provided in Annex 1.3.

3.2.3 Eligibility criteria

Studies were considered eligible if they examined attendees or workers at major outdoor or semi-outdoor mass gathering events conducted in hot or chronically hot environments. Eligible populations included older adults, children, pregnant people, individuals with chronic disease or disability, culturally and linguistically diverse community members and visitors not acclimatized to heat. Events included major sporting events as well as large religious, cultural, political or festival gatherings.

Eligible interventions comprised event-level implementation of tailored heat-risk communication, mechanisms for identifying vulnerable participants and prioritizing support, and/or wearable alert tools designed to detect environmental heat exposure or physiological strain. Tailored communication included culturally and linguistically adapted messaging delivered before or during events, with specific behavioural guidance and information on on-site medical services. Vulnerability identification mechanisms included pre-registration screening, self-identification, medical screening or special ticket categories linked to prioritized support. Wearable alert tools included devices with defined alert thresholds and response pathways. Generic heat-related messaging without adaptation, interventions that did not target or identify vulnerable populations, or wearables without defined thresholds or response protocols were not considered eligible interventions.

Comparators included standard one-size-fits-all heat communication, absence of targeted vulnerability identification, and absence of wearable alerts or pre-implementation periods in before–after studies.

Eligible outcomes included HRI and dehydration in the overall population and within identified vulnerable subgroups. Cognitive and behavioural outcomes included knowledge, attitudes, perceptions and protective behaviours related to heat exposure, such as hydration practices, use of cooling areas and help-seeking behaviour. The fasting status of populations examined was not reported in any of the literature assessed. Process outcomes included performance of vulnerability screening mechanisms and wearable alert systems, including sensitivity, specificity, proportion of high-risk participants correctly identified, alert performance, false alarms and response to alerts. Secondary outcomes included uptake, acceptability, feasibility, costs, equity implications and human rights considerations.

Only original empirical studies using quantitative, qualitative, mixed-methods or implementation science designs were eligible. Reviews, systematic reviews, meta-analyses, editorials, commentaries, conference abstracts without full papers, books and book chapters were excluded. Publications for which full text could not be retrieved after reasonable efforts were also excluded.

3.2.4 Information sources and search strategy

A comprehensive literature search was conducted in PubMed and Scopus, as for SR1. The search strategy combined controlled vocabulary terms and free-text keywords related to mass gatherings, heat-risk communication, behavioural interventions, vulnerability screening, wearable devices, alert systems and heat-related health outcomes. Search strategies were developed iteratively and refined through pilot searches. Boolean operators and truncation were used as appropriate. No restrictions were applied with respect to geographical region. The final searches were conducted on 16 January 2026, and the full search algorithms for each database are reported in Annex 2.3.

3.2.5 Study selection and screening

The two-stage screening process (title/abstract followed by full-text), use of ASReview, independent screening by two reviewers (MV; KM) (36, 37), piloting of eligibility criteria, resolution of discrepancies and application of a stopping rule, were conducted as described in SR1.2.5. Reasons for exclusion at the full-text stage were recorded and are reported in the PRISMA flow diagram (Fig. 5). Backward reference searching of all included full-text articles was also conducted.

3.2.6 Data extraction

Data extraction was performed independently by two reviewers (KM; MA) using a predefined and pilot-tested data extraction form, consistent with that described in SR1.2.6. Extracted variables included authorship, year of publication, country and event setting, study design, characteristics of the population including vulnerable subgroups, description of communication strategies, vulnerability identification mechanisms, wearable technologies and alert thresholds, behavioural and health outcomes, process indicators, equity considerations, feasibility, costs and user acceptability. Discrepancies were resolved through discussion or by a third reviewer

(ADF). The complete data extraction table is provided in Annex 3.4.

3.2.7 Risk of bias assessment

Risk of bias was assessed using the ROBINS-I tool (40), as most of the included studies evaluated behavioural and implementation interventions rather than prediction models. The assessment procedures, including independent evaluation by two reviewers (AC; GG) and the consensus-based resolution of discrepancies, used identical methodology to that detailed in SR1.2.7.

3.2.8 Data synthesis

The marked heterogeneity of the included studies in terms of design (cross-sectional surveys, retrospective operational case reports, knowledge, attitude, practice (KAP) studies), intervention type (multilingual messaging, SMS alerts, digital displays, mobile applications, WBGT-triggered notifications), outcome measures (knowledge scores, self-reported protective behaviours, clinical HRI counts, process indicators) and population composition, precluded a formal quantitative meta-analysis. A structured narrative synthesis was therefore conducted, guided by the SWiM reporting framework (41) and informed by principles of thematic synthesis for behavioural and communication interventions (161).

Extracted data (Annex 3.4) were organized thematically around the three core components of the intervention, identified using the PICO framework:

1. tailored heat-risk communication;
2. mechanisms for vulnerability identification; and
3. wearable alert tools linked to defined thresholds and response pathways.

Quantitative data reported within individual studies (e.g. proportions of attendees and spectators recognizing heatstroke symptoms, acceptability rates for SMS messaging, incidence of HRI among specific subgroups) were tabulated descriptively but not statistically pooled.

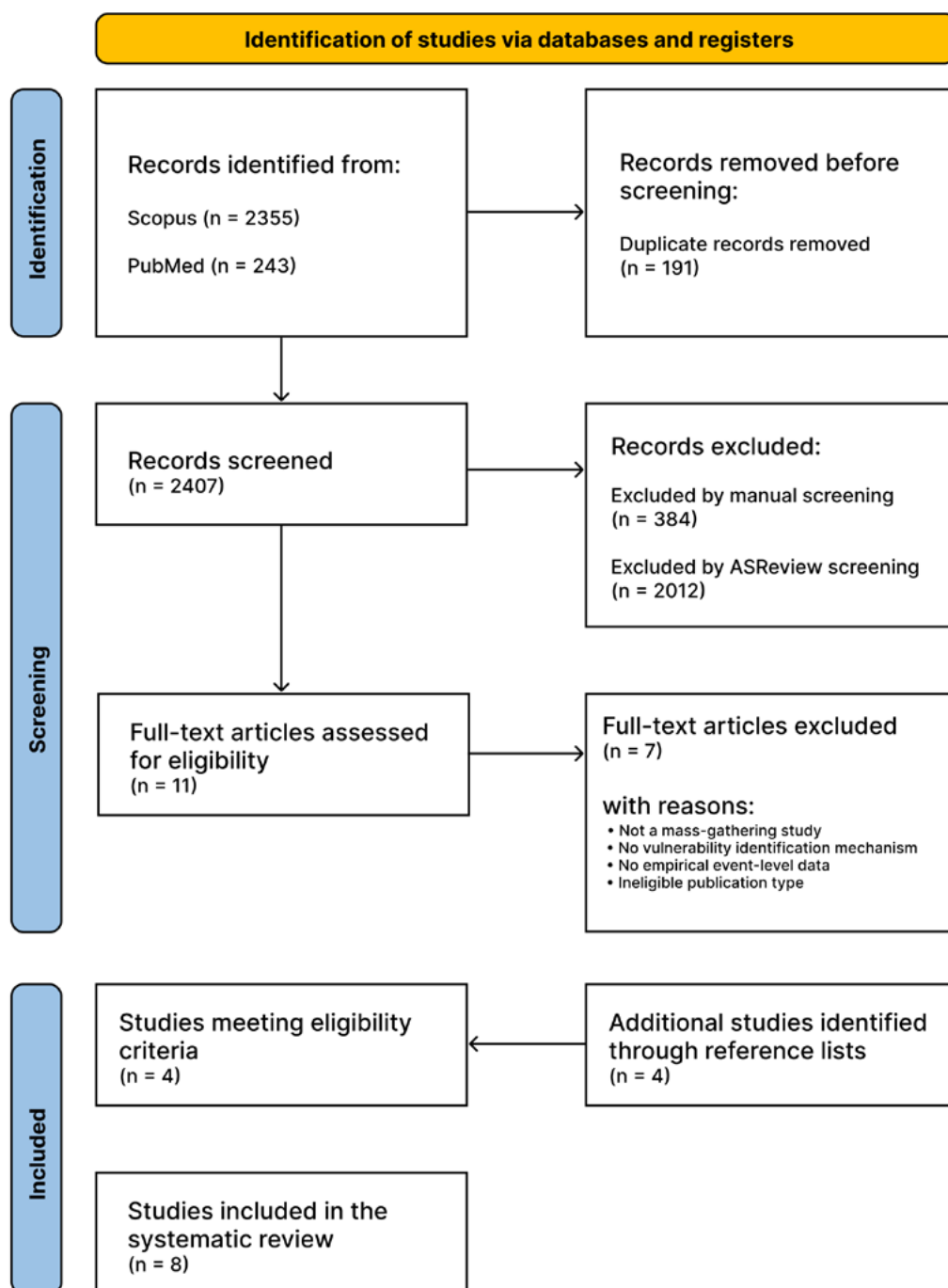
Process indicators for communication and alert systems, including sensitivity and specificity of any vulnerability identification mechanisms, alert performance and false alarm rates, were summarized where reported. Secondary outcomes (acceptability, feasibility, cost, equity and human rights considerations) were extracted and synthesized narratively across studies to identify recurrent barriers and enablers. The ROBINS-I judgements were integrated into the interpretation of findings, with particular attention to the domains of outcome measurement and confounding, which were most relevant for self-reported behavioural data. A notable gap-analysis component was also incorporated into the synthesis: the explicit documentation of PICO components (specifically, pre-event vulnerability screening registries and individualized wearable alert devices) for which no eligible empirical evidence was identified.

3.3 Results

A total of 2598 records were identified through our systematic search. The articles were written in 23 languages: 2464 in English, 46 in Chinese, 17 in German, 13 in French, 13 in Portuguese and 11 in Spanish. The remaining 38 articles (1.3% of total) were written in other languages. Following the removal of 191 duplicate records, 2407 records were screened, of which 2396 were excluded after title/abstract screening (384 manually and 2012 via ASReview). This resulted in 11 eligible reports sought for retrieval. Of the 11 full-text articles assessed for eligibility, 7 were excluded for various reasons including: not a mass gathering study, no vulnerability identification mechanism, no empirical event-level data, or being an ineligible publication type such as a review, letter or editorial. Consequently, four studies met the initial eligibility criteria. Four additional studies were identified through the screening of reference lists, yielding a final total of eight studies included in the systematic review.

Most of the included studies were observational cross-sectional studies or retrospective operational case reports. The studies were conducted across five countries (Japan, Malaysia, Saudi Arabia, the United Kingdom of Great Britain and Northern Ireland and the United States of America) and encompassed three categories of mass gatherings: religious pilgrimages (the Hajj, n=4), sporting events (the Super Bowl, US College Football and the Tokyo Olympics, n=3) and international exhibitions (Langkawi International Maritime and Aerospace Exhibition (LIMA) aerospace exhibition, n=1).

The cumulative attendance across the evaluated events exceeded 5 million individuals, representing highly diverse, multinational crowds. However, the specific study populations from which data were actively sampled (e.g. surveyed individuals or patients treated at clinics) amounted to approximately 3000 individuals.

Fig. 5. PRISMA flow diagram showing the study selection process for SR3^a

^a The flow chart details the systematic methodology for identifying, screening and selecting eligible studies for inclusion in the review.

3.3.1 Demographic and vulnerability characteristics

The demographic profiles of the populations studied reflected the specific contexts of the events. Religious mass gatherings, such as the Hajj (129, 162-164), were characterized by significantly older populations with high rates of pre-existing comorbidities. For instance, across the patients surveyed and clinically treated during the Hajj, up to 23.4% were over the age of 57 years, and underlying conditions such as hypertension (16.5%), diabetes (7.8%) and asthma (4.8%) were highly prevalent (129). These cohorts were exceptionally multinational, drawing pilgrims from regions spanning Africa, south-east Asia and Europe (129, 162, 163).

In contrast, sporting events (53, 66, 73, 165) and international exhibitions (76) generally attracted younger attendees, although older adult subgroups were still present. For example, during Super Bowl LVI (165), 14.5% of the surveyed cohort was over 65 years old, while the Tokyo Olympics (73) had a massive workforce population (<65 years) of nearly 313 000 non-athlete accreditation holders (including volunteers and security staff) working in extreme heat. None of the studies assessed provided information about the sex representation. In the Super Bowl LVI study (165), the respondents of the survey were predominantly female (65.5%).

Although the PICO questions explicitly focused on vulnerability identification, the extracted data reveal a critical gap: none of the eight included studies deployed formal pre-registration mechanisms or “vulnerability screening” tools to identify high-risk individuals before the events. Instead, vulnerabilities, such as age or chronic disease, were only identified retrospectively after a patient presented to a medical clinic (129, 164) or through post-event surveys (162, 165).

3.3.2 Tailored heat-risk communication and wearable alerts

The implementation of heat stress risk communication at the mass gatherings studied varied widely from generalized broadcasting to targeted digital messaging. Several events utilized multichannel, precision public health approaches. For example, the LIMA aerospace exhibition in Malaysia (76) utilized digital mobile apps, social media and on-site digital displays to disseminate real-time health advisories explicitly tailored to the tropical climate, focusing on hydration and the early signs of heat exhaustion. During Super Bowl LVI (162), public safety messages containing heat advisories were dispatched directly to participants via SMS texts.

For international events like the Hajj, communication was often culturally and linguistically tailored out of necessity. Efforts included multilingual billboards, pamphlets and direct face-to-face communication (163). However, the effectiveness of these campaigns was mixed; while Hajj pilgrims recognized heatstroke as a serious threat (78% of respondents in the study by Taibah et al. (2020) (163)), significant knowledge–practice gaps persisted.

Regarding digital alerts, the Tokyo Olympics (73) provided a notable example of environmental-based warning systems. Notifications based on the real-time WBGT were sent directly to the smartphones of both athletes and the non-athlete event workforce to trigger preventive behaviours. However, there was a complete absence of individualized wearable alert devices (e.g. smartwatches measuring personal skin temperature) linked to vulnerability response protocols across all eight studies.

3.3.3 Health, behavioural and process outcomes

Health outcomes were explicitly reported in the clinical studies. During the Tokyo Olympics (73), 125 HRIs were recorded among the non-athlete workforce: 71% were mild and 29% required moderate cooling, although none became critical. In the more extreme environment of the Hajj, severe HRIs were prevalent. Alkassas et al. (2021) (129) identified 231 confirmed or suspected HRIs, including 14 cases of heatstroke and 40 cases of heat exhaustion, predominantly affecting older adults with comorbidities.

Behavioural outcomes highlighted significant challenges in crowd compliance. A comprehensive KAP survey of Hajj pilgrims (162) revealed that while general knowledge of heat stress was moderate, actual protective practices were frequently inadequate. Many pilgrims remained unwilling to postpone physical rituals despite extreme heat warnings. Furthermore, an evaluation of clinical adherence among Hajj health care workers (164) found only average to below-average compliance with established HRI management guidelines, particularly regarding early fluid resuscitation and rapid active cooling for heatstroke.

Process indicators for communication tools yielded mixed results. The Super Bowl SMS study (165) found that while 84% of respondents favoured text messaging as an emergency communication modality, receiving the public safety message did not show a statistically significant association with proactive safety behaviours.

3.3.4 Equity, feasibility and acceptability

Data on equity, cost and feasibility were extremely limited. Universal access to medical care and messaging was generally implied across the events. In the case of the Tokyo Olympics (73), alerts on prevention of heat-related health problems were universally distributed across all accreditation holders regardless of role. Multilingual strategies (76) were actively deployed to ensure equitable access to information among diverse crowds.

However, cultural and structural barriers to equity were noted. Taibah et al. (2020) (163) reported significant difficulties in surveying female pilgrims due to Middle Eastern cultural norms limiting public interaction between the sexes, resulting in a heavily male-skewed sample (only 11.4% female).

Finally, the acceptability of digital messaging modalities (e.g. SMS) was generally high among users (165). However, the operational feasibility of robust clinical management was frequently hampered by the sheer volume and rush of the crowd, leading to incomplete medical documentation and difficulties in tracking patient outcomes (164).

3.3.5 Risk of bias

The methodological quality of the eight included studies was assessed using the ROBINS-I tool, revealing a generally acceptable risk of bias profile. Overall, five studies (63%) were judged to have a low risk of bias, while the remaining three studies (38%) demonstrated a moderate risk (Fig.6a and 6b). Notably, no studies were assessed as having a serious or critical risk of bias. When evaluating specific domains, the selection of the reported result demonstrated the highest methodological rigour, with 100% of the studies rated as low risk. The primary drivers contributing to the moderate risk classifications were the measurement of outcomes

(38% moderate risk) and confounding (25% moderate risk). From a qualitative perspective, this reflects the inherent challenges of evaluating behavioural and communication interventions at mass gatherings. Studies frequently relied on cross-sectional or self-reported survey data, which are highly susceptible to recall bias when capturing protective behaviours or attitudes. Also, they often failed to control for unmeasured confounding variables such as individual exposure times or baseline health literacy. Additional minor methodological concerns were noted in the classification of interventions (25% moderate risk) and missing data (13% moderate risk; 13% no information).

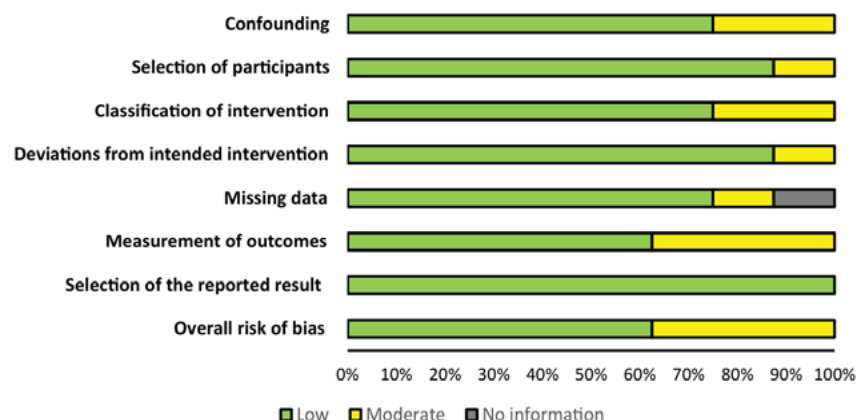
Fig. 6. Risk of bias assessment of the eight included studies using the ROBINS-I tool (a) and summary of judgements across specific bias domains (b)

(a)

	Confounding	Selection of participants	Classification of intervention	Deviations from intended intervention	Missing data	Measurement of outcomes	Selection of the reported result	Overall
Almuzaini 2021	-	-	-	+	-	-	+	-
Alkassas 2021	+	+	+	+	+	+	+	+
Collins 2024	+	+	+	+	+	+	+	+
Yezli 2019	-	+	-	+	?	-	+	-
J.Cadet 2023	+	+	+	+	+	+	+	+
A.I.A Rahim 2025	+	+	+	+	+	+	+	+
H.Taibah 2020	+	+	+	+	+	+	+	+
H.Tanaka 2023	+	+	+	-	+	-	+	-

+ Low risk
- Moderate risk
X Serious risk
! Extreme risk
? No information

(b)



3.4 Discussion

This systematic review synthesized evidence from eight studies encompassing more than 5 million attendees to evaluate the effectiveness of tailored heat-risk communication, vulnerability identification and wearable alert tools for high-risk populations at mass gatherings. Our findings highlight an important operational and evidence gap in the proactive management of vulnerable attendees. While event organizers frequently utilize multichannel, culturally tailored risk communication, there is a systemic gap in the literature regarding the proactive identification of vulnerable individuals according to the PROGRESS+ factors (place of residence, race/ethnicity, occupation, gender/sex, religion, education, socioeconomic status and social capital). Furthermore, the anticipated integration of personalized wearable alert systems for these high-risk subgroups is entirely absent from current empirical event evaluations, underscoring a stark divide between theoretical precision public health and real-world management of mass gatherings (18, 166).

A central and concerning finding of this review is the total absence of formal, pre-event vulnerability screening mechanisms. Despite the established epidemiological consensus that older adults and individuals with chronic diseases (such as hypertension and diabetes) bear the overwhelming burden of severe heat-related morbidity and mortality at mass gatherings (2, 32, 129, 167), none of the included studies deployed proactive registration or screening tools to identify these individuals before environmental exposure. Instead, vulnerability was consistently treated as a retrospective clinical observation, identified only after a patient presented to on-site medical services with an acute HRI (129, 162, 164). This reactive approach severely limits the ability of event medical directors to prioritize resources, such as targeted cooling interventions or prioritized evacuation routes, for those at greatest risk of heat-related collapse.

In the absence of individualized screening and wearable alerts, organizers have relied heavily on broad, tailored heat-risk communication strategies. The literature demonstrates a highly successful operational shift towards digital and multichannel messaging (168, 169). Events such as the LIMA aerospace exhibition and the Super Bowl effectively leveraged mobile applications, social media, digital displays and direct SMS text messaging to deliver real-time health advisories (76, 165). Similarly, the Tokyo Olympics successfully integrated environmental sensing into their communication strategy by pushing automated WBGT-based alerts to the smartphones of staff and volunteers operating in extreme heat (73).

However, evaluating these communication interventions reveals a well-documented behavioural phenomenon known as the knowledge–action gap or intention–behaviour gap, although the magnitude of this gap can be influenced by communication approaches (169, 170). While digital health advisories are highly acceptable to attendees, with 84% of Super Bowl respondents favouring emergency SMS alerts (165), receiving these messages does not reliably translate into protective behavioural changes. For instance, the SMS alerts at the Super Bowl did not lead to a statistically significant association with proactive safety behaviours (165). This disconnect is even more pronounced in religious and cultural mass gatherings. A comprehensive survey of Hajj pilgrims revealed that, although general knowledge of heat stress (and the fear of heatstroke) was remarkably high, actual protective practices were dangerously inadequate (162, 163). Many pilgrims explicitly refused to alter or postpone physical rituals despite extreme heat warnings (162). This suggests that informational risk communication alone is insufficient. Determinants of

non-adherence in this setting are likely to include ritual obligation, logistic constraint, cognitive overload and possibly heat-induced cognitive impairment; the relative contribution of each remains insufficiently characterized by primary qualitative evidence (7, 17, 171).

Furthermore, the data suggested that communication and training deficits extend beyond the attendees to the health care responders themselves. In the chaotic, high-volume environment of mass gatherings, clinical adherence to established heat-illness management guidelines can falter. Almuzaini et al. (2021) highlighted that health care workers demonstrated below-average compliance with advanced heat exhaustion and pre-hospital heatstroke management protocols, frequently failing to initiate rapid active cooling or early fluid resuscitation (164). This underscores that tailored communication must also incorporate robust, digitally supported clinical decision-support systems for event paramedics and first responders.

Finally, ensuring equity in heat-risk communication remains a complex challenge. While universal access to digital messaging was a common operational goal (73, 76), structural and cultural barriers frequently excluded key groups of mass gathering attendees. Multilingual strategies are essential but difficult to scale perfectly, and cultural norms, such as gender segregation constraints reported in surveys at religious pilgrimages, can systematically exclude specific populations from risk perception data (163, 172). WHO emphasizes that early warning and communication systems must be inherently equitable, ensuring that life-saving information is accessible regardless of language, literacy level or gender (18).

Ultimately, current strategies for addressing heat stress risk at mass gatherings rely heavily on one-way digital communication that informs but frequently fails to protect. Future research must urgently shift towards “precision mass gathering medicine”. This requires the development and validation of pre-event vulnerability screening registries and the deployment of targeted, personalized wearable alert devices that not only detect individual physiological strain but also trigger immediate, culturally resonant behavioural prompts to prevent clinical emergencies.

3.5 Limitations

This systematic review is subject to several significant limitations, largely driven by the scarcity and limited scope of the available primary literature. The most critical limitation is the sheer lack of empirical data directly addressing the core PICO question, which limits the robustness of the conclusions and highlights the need for further research in this area. Despite conducting a comprehensive search, no studies were identified that explicitly evaluated the implementation of pre-event vulnerability screening registries or the deployment of personalized wearable alert devices linked to protective behavioural outcomes at mass gatherings. Consequently, the synthesized evidence relies exclusively on studies evaluating broader, population-level heat-risk communication strategies, precluding any definitive conclusions regarding the efficacy of targeted, individualized interventions for vulnerable subgroups.

Additionally, the methodological quality and study design of the included studies constrain the strength of the findings. Most of the eight included studies utilized observational, cross-sectional or retrospective case report designs. These methodologies are inherently susceptible to unmeasured confounding and recall bias, particularly when evaluating subjective outcomes such as self-reported behavioural changes, knowledge acquisition and attitudes towards digital health messaging (162, 163, 165). Furthermore, the lack of controlled comparators (such as comparing a group receiving a tailored SMS warning against a group receiving generic warnings) severely limits the ability to establish causal relationships between the communication interventions and the observed behavioural or clinical outcomes.

Similar to the findings in **SR1** and **SR2**, there is a pronounced geographical, sex and cultural skew in the evidence base. Half of the included studies (50%) were conducted within the specific context of the Hajj pilgrimage in Saudi Arabia (129, 162-164). While these studies offer critical insights into managing extreme heat stress among older, multinational populations with comorbidities, the unique spiritual imperatives, rigid logistic constraints and cultural dynamics of the Hajj may limit the generalizability of these findings to secular mass gatherings, such as music festivals or international sporting events in different climatic zones, particularly to events where greater gender balance would be expected.

The review also identified significant demographic imbalances in the sampled populations. Structural and cultural barriers occasionally resulted in highly skewed cohorts, such as the severe underrepresentation of female attendees in survey data due to cultural restrictions on interactions between the sexes (163). Additionally, outcome data were frequently gathered only from attendees who formally interacted with digital platforms or actively sought medical care. This is likely to have led to a failure to capture the true behavioural responses and heat strain experienced by the broader, less engaged crowd.

Conclusion

This systematic review of 54 studies, spanning a cumulative mass gathering attendance of more than 70 million individuals, underscores that heat stress is no longer a peripheral logistic concern but a central determinant of public health security at mass gatherings. As climate change accelerates the frequency, duration and intensity of extreme heat events, the traditional paradigm of medical management at mass gatherings, which has historically relied almost exclusively on reactive emergency response, must fundamentally evolve towards proactive, heat-health adaptation measures (173, 174).

The findings from **SR1** clearly establish that the clinical burden of HRI at mass gatherings is immense, generating nearly half a million recorded medical encounters and significant mortality across the evaluated literature. Crucially, this risk is not uniform; it is heavily influenced by a unique “risk signature” defined by the demographic and cultural context of the event. Older populations with comorbidities who participate in religious pilgrimages in extreme climates (44, 55, 63) face an acutely elevated risk of severe heatstroke and mass mortality, requiring highly specialized, immediate, active cooling interventions. Conversely, younger cohorts at secular events face compounded risks from substance intoxication and trauma (48, 49, 51). While robust on-site medical infrastructure, particularly the deployment of tiered field hospitals and rapid on-site cooling, remains the most effective and cost-efficient method for preventing the need for hospital transfers, these structural interventions are persistently undermined by attendee non-compliance and deep-rooted behavioural barriers (55, 57).

SR2 demonstrates that the digital health ecosystem, driven by AI, IoMT and real-time data infrastructures, offers important potential to bridge this gap by transitioning event management from reactive to anticipatory. The successful deployment of large-scale digital syndromic surveillance systems linked directly to operational command (128) proves that real-time, data-driven resource reallocation is highly feasible. However, most emerging predictive technologies and AI-enabled wearable sensors remain confined to localized pilot phases. These individualized tools demonstrate high technical accuracy but are frequently validated on unrepresentative, healthy micro-cohorts (130-132) and lack the critical “closed-loop” integration with crowd-safety protocols necessary to function as true early warning systems.

Finally, **SR3** exposes the most critical operational gap in current heat adaptation strategies: the systemic failure to proactively identify and protect vulnerable subgroups before environmental exposure occurs. Despite the epidemiological consensus that older adults and those with chronic diseases bear the brunt of severe heat-related morbidity, none of the evaluated literature demonstrated the use of pre-event vulnerability screening registries or targeted wearable alerts linked to protective behaviours. Instead, organizers rely on broad, multichannel risk communication (73, 76, 165), which, while technologically sophisticated and highly acceptable to users, frequently fails to overcome the “knowledge-action gap” (162-164).

The available evidence suggests that these strategies do not consistently translate awareness into protective action; the contributing mechanisms, including ritual obligation, logistic constraints, cognitive overload and possibly heat-induced cognitive impairment, remain insufficiently studied.

Prevention and management of HRIs in the context of mass gatherings will require integrating the on-site clinical infrastructure described in SR1, the real-time digital surveillance frameworks examined in SR2, and the targeted behavioural and communication approaches reviewed in SR3 – what some authors have termed “precision mass-gathering medicine”. Priorities for future research and global health guidance include: (i) developing and evaluating culturally adapted, pre-event vulnerability identification mechanisms; (ii) validating integrated, multimodal early warning systems that link environmental sensing and physiological monitoring to defined operational response pathways; and (iii) measuring clinical and operational outcomes, including incidence of HRI, time-to-cooling, hospital transfer and mortality.

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Annex 1

Research questions and population, intervention, comparator and outcome (PICO) methodology

Annex 1.1 PICO 1 – Cooling infrastructure, cool rest zones, cooling breaks and hydration practices

PICO 1. Cooling infrastructure, cool rest zones, cooling breaks and hydration practices (addresses Q1, Q2, Q3 and Q4)

PICO question: Among spectators, volunteers and staff at mass gathering events held in hot or chronically hot environments (**P**), does exposure to enhanced cooling infrastructure, cool rest zones, cooling breaks and culturally appropriate hydration support (**I**), compared with standard practice (**C**), reduce heat-related illness and heat stress among spectators, volunteers and staff (**O**)?

Population	Attendees, volunteers, security and other workers during mass gatherings in hot or chronically hot environments, or during periods of high heat ¹ <i>Stratifiers:</i> type of mass gathering events (sporting, religious, cultural, political and other)
Intervention	Events/venues or sub-areas where the following are implemented and used: • Temporary, low-cost and/or low-impact cooling infrastructure to treat individuals experiencing heat-related illness (e.g. safe water tanks, mobile cooling units, portable fans and other cooling modalities) • Temporary, low-cost and/or low-impact cooling infrastructure deployable at scale (e.g. portable cooling structures, tents, canopies, mobile cooling areas, portable fans, misting stations and other evaporative cooling points) designed for equitable access • Cool rest zones and cooling shelters (their design, location, size, capacity, staffing, operating models and rules) • Cooling breaks or pauses in events (their locations, timing, frequency and trigger thresholds) • Culturally appropriate hydration support (free safe drinking water, appropriate drink types, timing)

¹ A study/event is defined as occurring in “high heat” if it is explicitly defined as a heatwave/heat alert or meets a local percentile-based trigger, for example: $\geq 95^{\text{th}}\text{--}99^{\text{th}}$ percentile of a local heat-stress metric (temperature, apparent temperature, WBGT, heat index, etc.) as a proxy for health-relevant extremes when local exposure-response data are unavailable.

Comparator	Currently available standard of practice and equipment for out-of-hospital heatstroke treatment Various designs/levels of provision (e.g. fewer cooling structures, shorter or no cooling breaks, no misting stations or restricted access).
Outcome	Heat-related illness: heat exhaustion, heat syncope, heatstroke (classical and/or exertional), dehydration requiring care, collapse, emergency department visits, ambulance call-outs, general practitioner clinic presentations, hospitalization, deaths Physiological heat strain (e.g. core temperature, heart rate, wet bulb globe temperature (WBGT) index, length of time in direct sun) Use of on-site medical services, referrals and transfers Equity of access and benefit across subgroups (age, sex, gender, disability, socioeconomic status, travel origin, etc.) Costs Feasibility User acceptability

Annex 1.2 PICO 2 Integrated early warning, crowd/capacity management, mobile apps and dynamic heat sensing

PICO 2: Integrated early warning, crowd/capacity management, mobile apps and dynamic heat sensing (addresses Q5, Q9 and Q10)

PICO question: Among spectators, volunteers, staff, security and other workers, and local communities affected by major mass gathering events in hot or chronically hot environments (**P**), does exposure to integrated heat early-warning and real-time heat-risk management systems (linked to crowd management, ticketing/registration systems, mobile apps and dynamic heat sensing/mapping) (**I**), compared with less or non-integrated or minimal heat systems (**C**), reduce heat-related illness and unsafe crowd conditions (**O**)?

Population	All attendees, spectators, volunteers, security and other workers and local communities affected by major mass gathering events in hot or chronically hot environments¹ <i>Stratifiers:</i> type of mass gathering events (sporting, religious, cultural, political and other)
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¹ A study/event is defined as occurring in "high heat" if it is explicitly defined as a heatwave/heat alert or meets a local percentile-based trigger, for example: ≥ 95 th-99th percentile of a local heat-stress metric (temperature, apparent temperature, WBGT, heat index, etc.) as a proxy for health-relevant extremes when local exposure-response data are unavailable.

Intervention	Events that implement integrated systems where exposure assessment relies on empirical data collected locally (i.e. not remote weather stations, estimates or modelling), such as: • Heat early-warning systems linked to event-specific thresholds that trigger operational changes and predefined actions • Integration of heat warnings with crowd/flow management and logistics (e.g. controlled entry/exit, capacity limits, re-routing, opening/closing of zones, provision of extra cooling capacity in hot spots) • Integration with ticketing or registration platforms and mobile applications (personalized heat alerts, heat advisories, dynamic schedules, route guidance, gate times) that include directions to cooling stations • Dynamic crowd heat mapping using cameras, AI or aggregated wearable sensor data to identify high-risk locations in real time • Crowd-sensitive response protocols that define who responds, how fast and what actions (e.g. redistribution of crowds, activation of additional cooling stations, ambulance services, temporary suspension of play/spectating) are taken when thresholds are exceeded
Comparator	Mass gathering events without heat-specific early-warning systems, or with simple weather information only and no integration with operations Major sporting events with early warning but no dynamic mapping or no crowd-sensitive response protocols Pre- versus post-implementation periods for the same mass gathering event
Outcome	Heat-related health events (on-site presentations of heat-related illness symptoms, on-site treatment, hospitalizations, admissions to an intensive care unit, deaths) Crowd-safety incidents during hot conditions (e.g. fainting clusters, mass crashes, uncontrolled crowd movement triggered by heat) Timeliness and appropriateness of operational responses once thresholds are exceeded Human rights and health equity Costs Feasibility User acceptability

Annex 1.3 PICO 3 Visitor knowledge, behaviour, vulnerability identification and wearable alerts

PICO 3: Visitor knowledge, behaviour, vulnerability identification and wearable alerts (addresses Q2, Q6, Q7 and Q8)

PICO question: Among participants and workers (older adults, children, pregnant people, individuals with chronic disease or disability, culturally and linguistically diverse community members and heat-unacclimatized visitors) at mass gathering events in hot or chronically hot environments (**P**), does exposure to tailored heat-risk communication, vulnerability identification and wearable alert tools (**I**), compared with standard or generic approaches or no such tools (**C**), improve protective behaviours and reduce heat-related illness, especially among vulnerable groups (**O**)?

Population	Attendees and workers at mass gatherings held in hot or chronically hot environments, including older adults, children, pregnant people, individuals with chronic disease or disability, culturally and linguistically diverse community members, and heat-unacclimatized visitors <i>Stratifiers:</i> type of mass gathering (sporting, religious, cultural, political and other)
Intervention	One or more of the following implemented at event level Culturally and linguistically tailored heat-risk communication (before, during, and post-event), addressing: • messages adapted to different heat perceptions, languages and cultural practices, • specific guidance on hydration, clothing, sun protection, rest, cooling and early help-seeking, including map of on-site clinics. • Mechanisms to identify vulnerable participants (e.g. via pre-registration data, self-identification, on-site screening, medical screening, special ticket categories) and provide them with prioritized support (access to cooling, cool zones or medical care) • Wearable alert devices (smart watches, alert bracelets, tags or similar) that detect heat or physiological strain, with defined alert thresholds, types of alerts (visual, sound, vibration) and clear response pathways (who monitors data, who intervenes and how)

Comparator	Standard “one-size-fits-all” heat messaging, no or limited multilingual/cultural adaptation No targeted vulnerability identification or prioritization No wearable alerts, or wearables without defined thresholds or response pathways
Outcome	Heat-related illness and dehydration in the overall population and in identified vulnerable groups versus non-vulnerable subgroups Knowledge, attitudes, perceptions and behaviours related to heat (before and during the event) such as hydration practices, use of cool zones, help-seeking Uptake, acceptability and feasibility of vulnerability identification and wearable alert systems Process outcomes: sensitivity/specificity of vulnerability screening, alert performance, response to alerts Process indicators: proportion of high-risk participants correctly identified; proportion of alerts followed by appropriate response; false alarms and missed events Human rights and health equity Costs Feasibility User acceptability

Annex 2

Search strategy

The three search algorithms detailed below were used to query the PubMed database for systematic reviews 1, 2 and 3 and were subsequently adjusted for the Scopus database.

Annex 2.1 Systematic review 1 search algorithm

(attendee*[Title/Abstract] OR participant*[Title/Abstract] OR "event-goer"[Title/Abstract] OR "meeting attendee"[Title/Abstract] OR "conference attendee"[Title/Abstract] OR "festival-goer"[Title/Abstract] OR patron*[Title/Abstract] OR "audience member"[Title/Abstract] OR spectator*[Title/Abstract] OR viewer*[Title/Abstract] OR onlooker*[Title/Abstract] OR audience*[Title/Abstract] OR "crowd observer"[Title/Abstract] OR "sports fan"[Title/Abstract] OR "sports fans"[Title/Abstract] OR fan[Title/Abstract] OR fans[Title/Abstract] OR supporter*[Title/Abstract] OR staff[Title/Abstract] OR "event staff"[Title/Abstract] OR "event personnel"[Title/Abstract] OR "support staff"[Title/Abstract] OR "venue staff"[Title/Abstract] OR "temporary staff"[Title/Abstract] OR "security staff"[Title/Abstract] OR "medical staff"[Title/Abstract] OR "volunteer staff"[Title/Abstract] OR crew[Title/Abstract] OR organizer*[Title/Abstract] OR "organising committee"[Title/Abstract] OR "operations staff"[Title/Abstract] OR tourist*[Title/Abstract] OR traveller*[Title/Abstract] OR traveler*[Title/Abstract] OR visitor*[Title/Abstract] OR sightseer*[Title/Abstract] OR holidaymaker*[Title/Abstract] OR vacationer*[Title/Abstract] OR "pilgrim tourist"[Title/Abstract] OR visitor*[Title/Abstract] OR guest*[Title/Abstract] OR "guest attendee"[Title/Abstract] OR "public attendee"[Title/Abstract] OR "public visitor"[Title/Abstract] OR "entrance visitor"[Title/Abstract] OR volunteer*[Title/Abstract] OR "event volunteer"[Title/Abstract] OR "community volunteer"[Title/Abstract] OR "support volunteer"[Title/Abstract] OR "aid worker"[Title/Abstract] OR "first responder"[Title/Abstract] OR "medical volunteer"[Title/Abstract] OR worker*[Title/Abstract] OR employee*[Title/Abstract] OR "event worker"[Title/Abstract] OR "temporary worker"[Title/Abstract] OR "seasonal worker"[Title/Abstract] OR "security guard"[Title/Abstract] OR police[Title/Abstract] OR "law enforcement"[Title/Abstract] OR "emergency personnel"[Title/Abstract] OR "medical worker"[Title/Abstract] OR paramedic*[Title/Abstract] OR "first responder"[Title/Abstract] OR "crowd marshal"[Title/Abstract] OR usher*[Title/Abstract] OR pilgrim*[Title/Abstract] OR "religious pilgrim"[Title/Abstract] OR worshipper*[Title/Abstract] OR devotee*[Title/Abstract] OR "faith-based participant"[Title/Abstract] OR "Hajj pilgrim"[Title/Abstract] OR "Umrah pilgrim"[Title/Abstract] OR crowd*[Title/Abstract] OR "mass gathering"[Title/Abstract] OR "large crowd"[Title/Abstract] OR "dense crowd"[Title/Abstract] OR "public gathering"[Title/Abstract] OR "people gathering"[Title/Abstract] OR "human crowd"[Title/Abstract] OR "assembled crowd"[Title/Abstract] OR "local communit"[Title/Abstract] OR resident*[Title/Abstract] OR "local resident"[Title/Abstract] OR "neighbourhood resident"[Title/Abstract] OR "host communit"[Title/Abstract] OR "host population"[Title/Abstract] OR "local population"[Title/Abstract] OR "local people"[Title/Abstract] OR "nearby population"[Title/Abstract]

Abstract] OR "surrounding communit*" [Title/Abstract]) AND ("mass gathering*" [Title/Abstract] OR "religious gathering*" [Title/Abstract] OR Hajj [Title/Abstract] OR Mecca [Title/Abstract] OR "Kumbh Mela" [Title/Abstract] OR "Arba'in pilgrimage" [Title/Abstract] OR Arba'in [Title/Abstract] OR "Durga Puja" [Title/Abstract] OR "Feast of the Black Nazarene" [Title/Abstract] OR "Black Nazarene" [Title/Abstract] OR "Magh Mela" [Title/Abstract] OR "World Youth Day" [Title/Abstract] OR Donauinsselfest [Title/Abstract] OR Mawazine [Title/Abstract] OR "Quebec City Summer Festival" [Title/Abstract] OR Summerfest [Title/Abstract] OR Coachella [Title/Abstract] OR "Rock in Rio" [Title/Abstract] OR Tomorrowland [Title/Abstract] OR "Sydney New Year's Eve Concerts" [Title/Abstract] OR "Sziget Festival" [Title/Abstract] OR "Lollapalooza Chicago" [Title/Abstract] OR "Rio de Janeiro Carnival" [Title/Abstract] OR Carnival [Title/Abstract] OR Olympic* [Title/Abstract] OR "Olympic Games" [Title/Abstract] OR Games [Title/Abstract] OR "Summer Olympic*" [Title/Abstract] OR Paralympic* [Title/Abstract] OR "Special Games" [Title/Abstract] OR FIFA [Title/Abstract] OR "World Cup" [Title/Abstract] OR "World Championship*" [Title/Abstract] OR marathon* [Title/Abstract] OR "Tour de France" [Title/Abstract] OR "Grand Slam" [Title/Abstract] OR "Super Bowl" [Title/Abstract] OR "Cricket World Cup" [Title/Abstract] OR "Formula One" [Title/Abstract] OR "Formula 1" [Title/Abstract] OR Games [Title/Abstract] OR "Commonwealth Games" [Title/Abstract] OR "Pan American Games" [Title/Abstract] OR "Pan Am Games" [Title/Abstract] OR "African Games" [Title/Abstract] OR "All-Africa Games" [Title/Abstract] OR "Pan African Games" [Title/Abstract] OR "Pan-Asian Games" [Title/Abstract] OR "Asian Games" [Title/Abstract] OR "European Games" [Title/Abstract] OR "public event*" [Title/Abstract] OR "religious event*" [Title/Abstract] OR "religious gathering*" [Title/Abstract] OR "semi-outdoor event*" [Title/Abstract] OR "athletic event*" [Title/Abstract] OR amusement [Title/Abstract] OR "sport event*" [Title/Abstract] OR "sporting event*" [Title/Abstract] OR pilgrimage* [Title/Abstract] OR concert* [Title/Abstract] OR gig [Title/Abstract] OR gigs [Title/Abstract] OR rockfest [Title/Abstract] OR "cultural event*" [Title/Abstract] OR "endurance event*" [Title/Abstract] OR fair* [Title/Abstract] OR festival* [Title/Abstract] OR festiv* [Title/Abstract] OR recreation [Title/Abstract] OR "large scale event*" [Title/Abstract] OR "large-scale event*" [Title/Abstract] OR "marathon event*" [Title/Abstract] OR "mass event*" [Title/Abstract] OR "mass gathering*" [Title/Abstract] OR "mass participation event*" [Title/Abstract] OR "mega event*" [Title/Abstract] OR "mega-event*" [Title/Abstract] OR "mega sporting event*" [Title/Abstract] OR "mega-sporting event*" [Title/Abstract] OR "mega sport event*" [Title/Abstract] OR "mega-sport event*" [Title/Abstract] OR "music festival*" [Title/Abstract] OR "outdoor event*" [Title/Abstract] OR parade* [Title/Abstract] OR competition* [Title/Abstract] OR fiesta* [Title/Abstract] OR jubilee [Title/Abstract] OR ceremon* [Title/Abstract] OR procession* [Title/Abstract] OR spectacle* [Title/Abstract] OR exhibition* [Title/Abstract] OR fanfare* [Title/Abstract]) AND ("heat mitigation*" [Title/Abstract] OR "heat-related mitigation*" [Title/Abstract] OR "heat intervention*" [Title/Abstract] OR "heat-related intervention*" [Title/Abstract] OR "heat solution*" [Title/Abstract] OR "heat-related solution*" [Title/Abstract] OR "heat relief" [Title/Abstract] OR canopy* [Title/Abstract] OR shad* [Title/Abstract] OR sunshade* [Title/Abstract] OR "shade area*" [Title/Abstract] OR "shade structure*" [Title/Abstract] OR "shaded area*" [Title/Abstract] OR "shaded rest area*" [Title/Abstract] OR "shaded rest zone*" [Title/Abstract] OR tent* [Title/Abstract] OR marquee* [Title/Abstract] OR cover* [Title/Abstract] OR umbrella* [Title/Abstract] OR headgear [Title/Abstract] OR hat [Title/Abstract] OR hats [Title/Abstract] OR cloth* [Title/Abstract] OR cap [Title/Abstract] OR caps [Title/Abstract] OR "heat break*" [Title/Abstract] OR "heat break*" [Title/Abstract] OR break* [Title/Abstract] OR "rest break*" [Title/Abstract] OR "rest break*" [Title/Abstract] OR acclimat* [Title/Abstract] OR electrolyte* [Title/Abstract] OR water [Title/Abstract] OR drink* [Title/Abstract] OR "drinking water" [Title/Abstract] OR hydrat* [Title/Abstract] OR "water

station*[Title/Abstract] OR "cold water"[Title/Abstract] OR "cold water ingestion"[Title/Abstract] OR "ice slurry ingestion"[Title/Abstract] OR slurry[Title/Abstract] OR ice[Title/Abstract] OR coldpack[Title/Abstract] OR fluid[Title/Abstract] OR slush*[Title/Abstract] OR ingest*[Title/Abstract] OR cold[Title/Abstract] OR cooling*[Title/Abstract] OR cool*[Title/Abstract] OR precool*[Title/Abstract] OR "pre-cool*[Title/Abstract] OR midcool*[Title/Abstract] OR "per-cool*[Title/Abstract] OR percool*[Title/Abstract] OR "cooling intervention"[Title/Abstract] OR "cooling break*[Title/Abstract] OR "cooling center*[Title/Abstract] OR "cooling clothing"[Title/Abstract] OR "cooling infrastructure"[Title/Abstract] OR "cooling shelter*[Title/Abstract] OR "cooling station*[Title/Abstract] OR "cooling tent*[Title/Abstract] OR "cooling zone*[Title/Abstract] OR "cooling unit*[Title/Abstract] OR "water tank*[Title/Abstract] OR immers*[Title/Abstract] OR "cold water immersion"[Title/Abstract] OR "cold-water immersion"[Title/Abstract] OR cryotherapy[Title/Abstract] OR chill*[Title/Abstract] OR "evaporative cool*[Title/Abstract] OR "mist spray*[Title/Abstract] OR "misting station*[Title/Abstract] OR "skin wetting"[Title/Abstract] OR "skin misting"[Title/Abstract] OR misting[Title/Abstract] OR spray[Title/Abstract] OR fan[Title/Abstract] OR fans[Title/Abstract] OR "air condition*[Title/Abstract] OR dehumidificat*[Title/Abstract] OR convect*[Title/Abstract] OR ventilat*[Title/Abstract] OR HVAC[Title/Abstract]) AND ("Emergency Department visit*[Title/Abstract] OR "ED visit*[Title/Abstract] OR "ICU admission*[Title/Abstract] OR "ambulance call out*[Title/Abstract] OR hospitalization*[Title/Abstract] OR "on-site treatment"[Title/Abstract] OR "on-site medical services"[Title/Abstract] OR referrals[Title/Abstract] OR "hospital admission*[Title/Abstract] OR hospitalization*[Title/Abstract] OR "ambulance call*[Title/Abstract] OR "heat illness*[Title/Abstract] OR "heat injur*[Title/Abstract] OR "heat related illness*[Title/Abstract] OR "heat-related illness*[Title/Abstract] OR "heat stress disorder*[Title/Abstract] OR "heat stress disorder*[Title/Abstract] OR miliaria[Title/Abstract] OR "heat rash*[Title/Abstract] OR dermatoses[Title/Abstract] OR "heat fatigue"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heat syncope"[Title/Abstract] OR collapse[Title/Abstract] OR fainting[Title/Abstract] OR dizziness[Title/Abstract] OR "heat cramps"[Title/Abstract] OR "heat oedema"[Title/Abstract] OR "heat edema"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heatstroke"[Title/Abstract] OR "exertional heatstroke"[Title/Abstract] OR "classical heatstroke"[Title/Abstract] OR disorientation[Title/Abstract] OR aggressiv*[Title/Abstract] OR seizure*[Title/Abstract] OR coma[Title/Abstract] OR "organ damage"[Title/Abstract] OR "tissue damage"[Title/Abstract] OR coagulopathy[Title/Abstract] OR "systemic inflammatory response syndrome"[Title/Abstract] OR "heat-induced dyslipidaemia"[Title/Abstract] OR "fluid imbalance*[Title/Abstract] OR "electrolyte imbalance*[Title/Abstract] OR hypohydration[Title/Abstract] OR dehydration[Title/Abstract] OR "kidney disease*[Title/Abstract] OR "kidney disfunction"[Title/Abstract] OR "kidney injur*[Title/Abstract] OR "acute kidney injur*[Title/Abstract] OR "chronic kidney injur*[Title/Abstract] OR "kidney stones"[Title/Abstract] OR death*[Title/Abstract] OR "core temperature"[Title/Abstract] OR "body temperature"[Title/Abstract] OR "core body temperature"[Title/Abstract] OR "body core temperature"[Title/Abstract] OR "rectal temperature"[Title/Abstract] OR "skin temperature"[Title/Abstract] OR "heart rate"[Title/Abstract] OR sweat[Title/Abstract] OR hyperthermia[Title/Abstract] OR "physiological heat strain"[Title/Abstract] OR "heat strain"[Title/Abstract] OR dehydration[Title/Abstract] OR "cardiovascular strain"[Title/Abstract] OR cognition[Title/Abstract] OR "cognitive performance"[Title/Abstract] OR "thermal comfort"[Title/Abstract] OR "thermal sensation"[Title/Abstract] OR "thermal perception"[Title/Abstract] OR "perceived heat"[Title/Abstract] OR heat[Title/Abstract] OR "heat stress"[Title/Abstract] OR "heat exposure"[Title/Abstract] OR "heat exposure condition*[Title/Abstract] OR "environmental heat"[Title/Abstract]

Abstract] OR "environmental temperature"[Title/Abstract] OR "hot condition*" [Title/Abstract] OR "excess heat"[Title/Abstract] OR "thermal load"[Title/Abstract] OR "thermal stress"[Title/Abstract] OR "thermal strain"[Title/Abstract] OR "hot environment*" [Title/Abstract] OR "high temperature environment*" [Title/Abstract] OR "high-temperature environment*" [Title/Abstract] OR "hot climatic condition*" [Title/Abstract] OR "extreme temperature"[Title/Abstract] OR "high heat"[Title/Abstract] OR "high-heat"[Title/Abstract] OR "extreme heat"[Title/Abstract] OR temperature*[Title/Abstract] OR "high temperature*" [Title/Abstract] OR "Wet Bulb Globe Temperature"[Title/Abstract] OR WBGT[Title/Abstract] OR "heat index"[Title/Abstract] OR "heat stress index"[Title/Abstract] OR "environmental heat index"[Title/Abstract] OR "thermal stress index"[Title/Abstract] OR "Universal Thermal Climate Index"[Title/Abstract] OR UTCI[Title/Abstract] OR humid*[Title/Abstract] OR "relative humidity"[Title/Abstract] OR "humid heat exposure"[Title/Abstract])

Annex 2.2 Systematic review 2 search algorithm

(attendee*[Title/Abstract] OR participant*[Title/Abstract] OR "event-goer*" [Title/Abstract] OR "meeting attendee*" [Title/Abstract] OR "conference attendee*" [Title/Abstract] OR "festival-goer*" [Title/Abstract] OR patron*[Title/Abstract] OR "audience member*" [Title/Abstract] OR spectator*[Title/Abstract] OR viewer*[Title/Abstract] OR onlooker*[Title/Abstract] OR audience*[Title/Abstract] OR "crowd observer*" [Title/Abstract] OR "sports fan"[Title/Abstract] OR "sports fans"[Title/Abstract] OR fan[Title/Abstract] OR fans[Title/Abstract] OR supporter*[Title/Abstract] OR staff[Title/Abstract] OR "event staff"[Title/Abstract] OR "event personnel"[Title/Abstract] OR "support staff"[Title/Abstract] OR "venue staff"[Title/Abstract] OR "temporary staff"[Title/Abstract] OR "security staff"[Title/Abstract] OR "medical staff"[Title/Abstract] OR "volunteer staff"[Title/Abstract] OR crew[Title/Abstract] OR organizer*[Title/Abstract] OR "organising committee"[Title/Abstract] OR "operations staff"[Title/Abstract] OR tourist*[Title/Abstract] OR traveller*[Title/Abstract] OR traveler*[Title/Abstract] OR visitor*[Title/Abstract] OR sightseer*[Title/Abstract] OR holidaymaker*[Title/Abstract] OR vacationer*[Title/Abstract] OR "pilgrim tourist*" [Title/Abstract] OR visitor*[Title/Abstract] OR guest*[Title/Abstract] OR "guest attendee*" [Title/Abstract] OR "public attendee*" [Title/Abstract] OR "public visitor*" [Title/Abstract] OR "entrance visitor*" [Title/Abstract] OR volunteer*[Title/Abstract] OR "event volunteer*" [Title/Abstract] OR "community volunteer*" [Title/Abstract] OR "support volunteer*" [Title/Abstract] OR "aid worker*" [Title/Abstract] OR "first responder*" [Title/Abstract] OR "medical volunteer*" [Title/Abstract] OR worker*[Title/Abstract] OR employee*[Title/Abstract] OR "event worker*" [Title/Abstract] OR "temporary worker*" [Title/Abstract] OR "seasonal worker*" [Title/Abstract] OR "security guard*" [Title/Abstract] OR police[Title/Abstract] OR "law enforcement"[Title/Abstract] OR "emergency personnel"[Title/Abstract] OR "medical worker*" [Title/Abstract] OR paramedic*[Title/Abstract] OR "first responder*" [Title/Abstract] OR "crowd marshal*" [Title/Abstract] OR usher*[Title/Abstract] OR pilgrim*[Title/Abstract] OR "religious pilgrim*" [Title/Abstract] OR worshipper*[Title/Abstract] OR devotee*[Title/Abstract] OR "faith-based participant*" [Title/Abstract] OR "Hajj pilgrim*" [Title/Abstract] OR "Umrah pilgrim*" [Title/Abstract] OR crowd*[Title/Abstract] OR "mass gathering*" [Title/Abstract] OR "large crowd*" [Title/Abstract] OR "dense crowd*" [Title/Abstract] OR "public gathering*" [Title/Abstract] OR "people gathering*" [Title/Abstract] OR "human crowd*" [Title/Abstract] OR "assembled crowd*" [Title/Abstract] OR "local communit*" [Title/Abstract] OR resident*[Title/Abstract] OR "local resident*" [Title/Abstract] OR "neighbourhood resident*" [Title/Abstract] OR

"host communit*" [Title/Abstract] OR "host population" [Title/Abstract] OR "local population" [Title/Abstract] OR "local people" [Title/Abstract] OR "nearby population" [Title/Abstract] OR "surrounding communit*" [Title/Abstract]) AND ("mass gathering*" [Title/Abstract] OR "religious gathering*" [Title/Abstract] OR Hajj [Title/Abstract] OR Mecca [Title/Abstract] OR "Kumbh Mela" [Title/Abstract] OR "Arba'in pilgrimage" [Title/Abstract] OR Arba'in [Title/Abstract] OR "Durga Puja" [Title/Abstract] OR "Feast of the Black Nazarene" [Title/Abstract] OR "Black Nazarene" [Title/Abstract] OR "Magh Mela" [Title/Abstract] OR "World Youth Day" [Title/Abstract] OR Donauinselt [Title/Abstract] OR Mawazine [Title/Abstract] OR "Quebec City Summer Festival" [Title/Abstract] OR Summerfest [Title/Abstract] OR Coachella [Title/Abstract] OR "Rock in Rio" [Title/Abstract] OR Tomorrowland [Title/Abstract] OR "Sydney New Year's Eve Concerts" [Title/Abstract] OR "Sziget Festival" [Title/Abstract] OR "Lollapalooza Chicago" [Title/Abstract] OR "Rio de Janeiro Carnival" [Title/Abstract] OR Carnival [Title/Abstract] OR Olympic* [Title/Abstract] OR "Olympic Games" [Title/Abstract] OR Games [Title/Abstract] OR "Summer Olympic*" [Title/Abstract] OR Paralympic* [Title/Abstract] OR "Special Games" [Title/Abstract] OR FIFA [Title/Abstract] OR "World Cup" [Title/Abstract] OR "World Championship*" [Title/Abstract] OR marathon* [Title/Abstract] OR "Tour de France" [Title/Abstract] OR "Grand Slam" [Title/Abstract] OR "Super Bowl" [Title/Abstract] OR "Cricket World Cup" [Title/Abstract] OR "Formula One" [Title/Abstract] OR "Formula 1" [Title/Abstract] OR Games [Title/Abstract] OR "Commonwealth Games" [Title/Abstract] OR "Pan American Games" [Title/Abstract] OR "Pan Am Games" [Title/Abstract] OR "African Games" [Title/Abstract] OR "All-Africa Games" [Title/Abstract] OR "Pan African Games" [Title/Abstract] OR "Pan-Asian Games" [Title/Abstract] OR "Asian Games" [Title/Abstract] OR "European Games" [Title/Abstract] OR "public event*" [Title/Abstract] OR "religious event*" [Title/Abstract] OR "religious gathering*" [Title/Abstract] OR "semi-outdoor event*" [Title/Abstract] OR "athletic event*" [Title/Abstract] OR amusement [Title/Abstract] OR "sport event*" [Title/Abstract] OR "sporting event*" [Title/Abstract] OR pilgrimage* [Title/Abstract] OR concert* [Title/Abstract] OR gig [Title/Abstract] OR gigs [Title/Abstract] OR rockfest [Title/Abstract] OR "cultural event*" [Title/Abstract] OR "endurance event*" [Title/Abstract] OR fair* [Title/Abstract] OR festival* [Title/Abstract] OR festiv* [Title/Abstract] OR recreation [Title/Abstract] OR "large scale event*" [Title/Abstract] OR "large-scale event*" [Title/Abstract] OR "marathon event*" [Title/Abstract] OR "mass event*" [Title/Abstract] OR "mass gathering*" [Title/Abstract] OR "mass participation event*" [Title/Abstract] OR "mega event*" [Title/Abstract] OR "mega-event*" [Title/Abstract] OR "mega sporting event*" [Title/Abstract] OR "mega-sporting event*" [Title/Abstract] OR "mega sport event*" [Title/Abstract] OR "mega-sport event*" [Title/Abstract] OR "music festival*" [Title/Abstract] OR "outdoor event*" [Title/Abstract] OR parade* [Title/Abstract] OR competition* [Title/Abstract] OR fiesta* [Title/Abstract] OR jubilee [Title/Abstract] OR ceremon* [Title/Abstract] OR procession* [Title/Abstract] OR spectacle* [Title/Abstract] OR exhibition* [Title/Abstract] OR fanfare* [Title/Abstract]) AND (alert* [Title/Abstract] OR "environment monitor*" [Title/Abstract] OR "environmental monitor*" [Title/Abstract] OR "early warning system*" [Title/Abstract] OR "heat risk alert*" [Title/Abstract] OR "heat stress alert*" [Title/Abstract] OR "heat warning*" [Title/Abstract] OR "heatwave warning*" [Title/Abstract] OR "heat early-warning" [Title/Abstract] OR "heat early warning" [Title/Abstract] OR "heat alert*" [Title/Abstract] OR notification* [Title/Abstract] OR threshold* [Title/Abstract] OR "thermal alert*" [Title/Abstract] OR "heat-risk management" [Title/Abstract] OR "heat risk management" [Title/Abstract] OR "heat advisor*" [Title/Abstract] OR guidance [Title/Abstract] OR recommendation* [Title/Abstract] OR "access control" [Title/Abstract] OR "capacity control" [Title/Abstract] OR "capacity management" [Title/Abstract] OR "controlled entry" [Title/Abstract] OR "controlled exit" [Title/Abstract] OR "crowd control" [Title/Abstract] OR "crowd

management"[Title/Abstract] OR "digital ticket*"[Title/Abstract] OR "e-ticket*"[Title/Abstract] OR "response protocol*"[Title/Abstract] OR "real-time assessment"[Title/Abstract] OR "real-time monitoring"[Title/Abstract] OR "real-time surveillance"[Title/Abstract] OR registration[Title/Abstract] OR "ticketing system*"[Title/Abstract] OR "video analytics"[Title/Abstract] OR "dynamic schedul*"[Title/Abstract] OR "dynamic route*"[Title/Abstract] OR "ambulance services"[Title/Abstract] OR "AI-based system*"[Title/Abstract] OR algorithm*[Title/Abstract] OR "artificial intelligence"[Title/Abstract] OR "machine learning"[Title/Abstract] OR "ML analysis"[Title/Abstract] OR "risk prediction"[Title/Abstract] OR "heat map*"[Title/Abstract] OR hotspot[Title/Abstract] OR "smartphone app*"[Title/Abstract] OR "digital platform*"[Title/Abstract] OR "mobile app*"[Title/Abstract] OR "body temperature sensor*"[Title/Abstract] OR "camera-based monitoring"[Title/Abstract] OR "computer vision"[Title/Abstract] OR "core temperature sensor*"[Title/Abstract] OR "environmental sensor*"[Title/Abstract] OR "heart rate sensor*"[Title/Abstract] OR "heart rate monitoring"[Title/Abstract] OR "infrared camera*"[Title/Abstract] OR "thermal camera*"[Title/Abstract] OR "skin temperature sensor*"[Title/Abstract] OR "temperature sensor*"[Title/Abstract] OR "wearable device*"[Title/Abstract] OR "wearable sensor*"[Title/Abstract] OR "biometric monitoring"[Title/Abstract] OR "wearable alert*"[Title/Abstract] OR "wearable device*"[Title/Abstract] OR "wearable sensor*"[Title/Abstract] OR "heat strain monitor*"[Title/Abstract] OR "thermal strain monitor*"[Title/Abstract] OR "vibration alert*"[Title/Abstract] OR "visual alert*"[Title/Abstract] OR "smart watch*"[Title/Abstract] OR "smart wearable*"[Title/Abstract] OR smartwatch*[Title/Abstract] OR "sound alert*"[Title/Abstract] OR "biometric monitoring"[Title/Abstract] OR "heat alert*"[Title/Abstract] OR "heat warning*"[Title/Abstract] OR "hydration advice"[Title/Abstract] OR "physiological monitor*"[Title/Abstract] OR "real time alert*"[Title/Abstract] OR "real-time alert*"[Title/Abstract]) AND ("Emergency Department visit*"[Title/Abstract] OR "ED visit*"[Title/Abstract] OR "ICU admission*"[Title/Abstract] OR "ambulance call out*"[Title/Abstract] OR hospitalization*[Title/Abstract] OR "on-site treatment"[Title/Abstract] OR "on-site medical services"[Title/Abstract] OR referrals[Title/Abstract] OR "hospital admission*"[Title/Abstract] OR hospitalization*[Title/Abstract] OR "ambulance call*"[Title/Abstract] OR "heat illness*"[Title/Abstract] OR "heat injur*"[Title/Abstract] OR "heat related illness*"[Title/Abstract] OR "heat-related illness*"[Title/Abstract] OR "heat stress disorder*"[Title/Abstract] OR "heat stress disorder*"[Title/Abstract] OR miliaria[Title/Abstract] OR "heat rash*"[Title/Abstract] OR dermatoses[Title/Abstract] OR "heat fatigue"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heat syncope"[Title/Abstract] OR collapse[Title/Abstract] OR fainting[Title/Abstract] OR dizziness[Title/Abstract] OR "heat cramps"[Title/Abstract] OR "heat oedema"[Title/Abstract] OR "heat edema"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heatstroke"[Title/Abstract] OR "exertional heatstroke"[Title/Abstract] OR "classical heatstroke"[Title/Abstract] OR disorientation[Title/Abstract] OR aggressiv*[Title/Abstract] OR seizure*[Title/Abstract] OR coma[Title/Abstract] OR "organ damage"[Title/Abstract] OR "tissue damage"[Title/Abstract] OR coagulopathy[Title/Abstract] OR "systemic inflammatory response syndrome"[Title/Abstract] OR "heat-induced dyslipidaemia"[Title/Abstract] OR "fluid imbalance*"[Title/Abstract] OR "electrolyte imbalance*"[Title/Abstract] OR hypohydration[Title/Abstract] OR dehydration[Title/Abstract] OR "kidney disease*"[Title/Abstract] OR "kidney disfunction"[Title/Abstract] OR "kidney injur*"[Title/Abstract] OR "acute kidney injur*"[Title/Abstract] OR "chronic kidney injur*"[Title/Abstract] OR "kidney stones"[Title/Abstract] OR death*[Title/Abstract] OR "crowd safety"[Title/Abstract] OR "crowd-safety"[Title/Abstract] OR crowd[Title/Abstract] OR "crowd dynamics"[Title/Abstract] OR "fainting clusters"[Title/Abstract] OR "mass crashes"[Title/Abstract] OR "uncontrolled crowd movement"[Title/Abstract] OR "pedestrian flow"[Title/Abstract] OR

evacuation[Title/Abstract] OR "emergency evacuation"[Title/Abstract] OR emergency[Title/Abstract] OR escape[Title/Abstract] OR transition[Title/Abstract] OR "jamming transition"[Title/Abstract] OR uncertainty[Title/Abstract] OR "decision making"[Title/Abstract] OR "social force model"[Title/Abstract] OR "cellular automaton model"[Title/Abstract] OR "cellular automaton"[Title/Abstract] OR "cellular automata"[Title/Abstract] OR "core temperature"[Title/Abstract] OR "body temperature"[Title/Abstract] OR "core body temperature"[Title/Abstract] OR "body core temperature"[Title/Abstract] OR "rectal temperature"[Title/Abstract] OR "skin temperature"[Title/Abstract] OR "heart rate"[Title/Abstract] OR sweat[Title/Abstract] OR hyperthermia[Title/Abstract] OR "physiological heat strain"[Title/Abstract] OR "heat strain"[Title/Abstract] OR dehydration[Title/Abstract] OR "cardiovascular strain"[Title/Abstract] OR cognition[Title/Abstract] OR "cognitive performance"[Title/Abstract] OR "thermal comfort"[Title/Abstract] OR "thermal sensation"[Title/Abstract] OR "thermal perception"[Title/Abstract] OR "perceived heat"[Title/Abstract] OR heat[Title/Abstract] OR "heat stress"[Title/Abstract] OR "heat exposure"[Title/Abstract] OR "heat exposure condition"[Title/Abstract] OR "environmental heat"[Title/Abstract] OR "environmental temperature"[Title/Abstract] OR "hot condition"[Title/Abstract] OR "excess heat"[Title/Abstract] OR "thermal load"[Title/Abstract] OR "thermal stress"[Title/Abstract] OR "thermal strain"[Title/Abstract] OR "hot environment"[Title/Abstract] OR "high temperature environment"[Title/Abstract] OR "high-temperature environment"[Title/Abstract] OR "hot climatic condition"[Title/Abstract] OR "extreme temperature"[Title/Abstract] OR "high heat"[Title/Abstract] OR "high-heat"[Title/Abstract] OR "extreme heat"[Title/Abstract] OR temperature*[Title/Abstract] OR "high temperature"[Title/Abstract] OR "Wet Bulb Globe Temperature"[Title/Abstract] OR WBGT[Title/Abstract] OR "heat index"[Title/Abstract] OR "heat stress index"[Title/Abstract] OR "environmental heat index"[Title/Abstract] OR "thermal stress index"[Title/Abstract] OR "Universal Thermal Climate Index"[Title/Abstract] OR UTCI[Title/Abstract] OR humid*[Title/Abstract] OR "relative humidity"[Title/Abstract] OR "humid heat exposure"[Title/Abstract])

Annex 2.3 Systematic review 3 search algorithm

(attendee*[Title/Abstract] OR participant*[Title/Abstract] OR "event-goer"[Title/Abstract] OR "meeting attendee"[Title/Abstract] OR "conference attendee"[Title/Abstract] OR "festival-goer"[Title/Abstract] OR patron*[Title/Abstract] OR "audience member"[Title/Abstract] OR spectator*[Title/Abstract] OR viewer*[Title/Abstract] OR onlooker*[Title/Abstract] OR audience*[Title/Abstract] OR "crowd observer"[Title/Abstract] OR "sports fan"[Title/Abstract] OR "sports fans"[Title/Abstract] OR fan[Title/Abstract] OR fans[Title/Abstract] OR supporter*[Title/Abstract] OR staff[Title/Abstract] OR "event staff"[Title/Abstract] OR "event personnel"[Title/Abstract] OR "support staff"[Title/Abstract] OR "venue staff"[Title/Abstract] OR "temporary staff"[Title/Abstract] OR "security staff"[Title/Abstract] OR "medical staff"[Title/Abstract] OR "volunteer staff"[Title/Abstract] OR crew[Title/Abstract] OR organizer*[Title/Abstract] OR "organising committee"[Title/Abstract] OR "operations staff"[Title/Abstract] OR tourist*[Title/Abstract] OR traveller*[Title/Abstract] OR traveler*[Title/Abstract] OR visitor*[Title/Abstract] OR sightseer*[Title/Abstract] OR holidaymaker*[Title/Abstract] OR vacationer*[Title/Abstract] OR "pilgrim tourist"[Title/Abstract] OR visitor*[Title/Abstract] OR guest*[Title/Abstract] OR "guest attendee"[Title/Abstract] OR "public attendee"[Title/Abstract] OR "public visitor"[Title/Abstract] OR "entrance visitor"[Title/Abstract] OR volunteer*[Title/Abstract] OR "event volunteer"[Title/Abstract] OR "community volunteer"[Title/Abstract] OR "support volunteer"[Title/Abstract] OR "aid worker"[Title/Abstract])

Abstract] OR "first responder*" [Title/Abstract] OR "medical volunteer*" [Title/Abstract] OR worker* [Title/Abstract] OR employee* [Title/Abstract] OR "event worker*" [Title/Abstract] OR "temporary worker*" [Title/Abstract] OR "seasonal worker*" [Title/Abstract] OR "security guard*" [Title/Abstract] OR police [Title/Abstract] OR "law enforcement" [Title/Abstract] OR "emergency personnel" [Title/Abstract] OR "medical worker*" [Title/Abstract] OR paramedic* [Title/Abstract] OR "first responder*" [Title/Abstract] OR "crowd marshal*" [Title/Abstract] OR usher* [Title/Abstract] OR pilgrim* [Title/Abstract] OR "religious pilgrim*" [Title/Abstract] OR worshipper* [Title/Abstract] OR devotee* [Title/Abstract] OR "faith-based participant*" [Title/Abstract] OR "Hajj pilgrim*" [Title/Abstract] OR "Umrah pilgrim*" [Title/Abstract] OR crowd* [Title/Abstract] OR "mass gathering*" [Title/Abstract] OR "large crowd*" [Title/Abstract] OR "dense crowd*" [Title/Abstract] OR "public gathering*" [Title/Abstract] OR "people gathering*" [Title/Abstract] OR "human crowd*" [Title/Abstract] OR "assembled crowd*" [Title/Abstract] OR "local communit*" [Title/Abstract] OR resident* [Title/Abstract] OR "local resident*" [Title/Abstract] OR "neighbourhood resident*" [Title/Abstract] OR "host communit*" [Title/Abstract] OR "host population" [Title/Abstract] OR "local population" [Title/Abstract] OR "local people" [Title/Abstract] OR "nearby population" [Title/Abstract] OR "surrounding communit*" [Title/Abstract] OR child* [Title/Abstract] OR infant* [Title/Abstract] OR baby [Title/Abstract] OR babies [Title/Abstract] OR toddler* [Title/Abstract] OR preschool* [Title/Abstract] OR schoolchild* [Title/Abstract] OR adolescent* [Title/Abstract] OR pediatric* [Title/Abstract] OR paediatric* [Title/Abstract] OR "chronic disease*" [Title/Abstract] OR "chronic illness*" [Title/Abstract] OR "long-term disease*" [Title/Abstract] OR "long-term condition*" [Title/Abstract] OR "non-communicable disease*" [Title/Abstract] OR "chronic health condition*" [Title/Abstract] OR comorbidit* [Title/Abstract] OR "multi-morbidit*" [Title/Abstract] OR multimorbidit* [Title/Abstract] OR "coexisting disease*" [Title/Abstract] OR "co-morbid condition*" [Title/Abstract] OR "multiple chronic condition*" [Title/Abstract] OR disabilit* [Title/Abstract] OR impairment* [Title/Abstract] OR "functional limitation*" [Title/Abstract] OR "activity limitation*" [Title/Abstract] OR "special needs" [Title/Abstract] OR "mobility limitation*" [Title/Abstract] OR "sensory impairment*" [Title/Abstract] OR "cognitive impairment*" [Title/Abstract] OR "intellectual disability*" [Title/Abstract] OR "learning disability*" [Title/Abstract] OR disabled [Title/Abstract] OR "people with disabilities" [Title/Abstract] OR "persons with disabilities" [Title/Abstract] OR "physically disabled" [Title/Abstract] OR "mentally disabled" [Title/Abstract] OR "mobility impaired" [Title/Abstract] OR "visually impaired" [Title/Abstract] OR "hearing impaired" [Title/Abstract] OR disease* [Title/Abstract] OR illness* [Title/Abstract] OR "medical condition*" [Title/Abstract] OR "health condition*" [Title/Abstract] OR "health disorder*" [Title/Abstract] OR patholog* [Title/Abstract] OR "high-risk group*" [Title/Abstract] OR "high risk population*" [Title/Abstract] OR "high risk individual*" [Title/Abstract] OR "risk group*" [Title/Abstract] OR "at-risk group*" [Title/Abstract] OR "vulnerable group*" [Title/Abstract] OR "susceptible population*" [Title/Abstract] OR migrant* [Title/Abstract] OR immigrant* [Title/Abstract] OR refugee* [Title/Abstract] OR "asylum seeker*" [Title/Abstract] OR "foreign worker*" [Title/Abstract] OR "displaced person*" [Title/Abstract] OR "mobile population*" [Title/Abstract] OR "temporary migrant*" [Title/Abstract] OR "older adult*" [Title/Abstract] OR "older people" [Title/Abstract] OR "older person*" [Title/Abstract] OR senior* [Title/Abstract] OR "senior citizen*" [Title/Abstract] OR "aging population" [Title/Abstract] OR "ageing population" [Title/Abstract] OR elderly [Title/Abstract] OR geriatric* [Title/Abstract] OR elder* [Title/Abstract] OR elderly [Title/Abstract] OR "older adult*" [Title/Abstract] OR "older people" [Title/Abstract] OR "aged population" [Title/Abstract] OR "frail elderly" [Title/Abstract] OR pregnan* [Title/Abstract] OR maternal [Title/Abstract] OR "expectant mother*" [Title/Abstract] OR "vulnerable population*" [Title/Abstract]

OR "vulnerable group*" [Title/Abstract] OR "at-risk population*" [Title/Abstract] OR
 "disadvantaged population*" [Title/Abstract] OR "marginalized population*" [Title/Abstract] OR
 "underserved population*" [Title/Abstract] OR "high-need population*" [Title/Abstract] OR
 "culturally and linguistically diverse" [Title/Abstract] OR "ethnic minorit*" [Title/Abstract] OR
 "linguistic minorit*" [Title/Abstract] OR "non-native speaker*" [Title/Abstract] OR "migrant
 communit*" [Title/Abstract] OR "minority population*" [Title/Abstract] OR "culturally diverse
 population*" [Title/Abstract] OR "multicultural communit*" [Title/Abstract]) AND ("mass
 gathering*" [Title/Abstract] OR "religious gathering*" [Title/Abstract] OR Hajj [Title/Abstract] OR
 Mecca [Title/Abstract] OR "Kumbh Mela" [Title/Abstract] OR "Arba'in pilgrimage" [Title/Abstract]
 OR Arba'in [Title/Abstract] OR "Durga Puja" [Title/Abstract] OR "Feast of the Black
 Nazarene" [Title/Abstract] OR "Black Nazarene" [Title/Abstract] OR "Magh Mela" [Title/Abstract]
 OR "World Youth Day" [Title/Abstract] OR Donauinsselfest [Title/Abstract] OR Mawazine [Title/
 Abstract] OR "Quebec City Summer Festival" [Title/Abstract] OR Summerfest [Title/Abstract] OR
 Coachella [Title/Abstract] OR "Rock in Rio" [Title/Abstract] OR Tomorrowland [Title/Abstract] OR
 "Sydney New Year's Eve Concerts" [Title/Abstract] OR "Sziget Festival" [Title/Abstract] OR
 "Lollapalooza Chicago" [Title/Abstract] OR "Rio de Janeiro Carnival" [Title/Abstract] OR
 Carnival [Title/Abstract] OR Olympic* [Title/Abstract] OR "Olympic Games" [Title/Abstract] OR
 Games [Title/Abstract] OR "Summer Olympic*" [Title/Abstract] OR Paralympic* [Title/Abstract]
 OR "Special Games" [Title/Abstract] OR FIFA [Title/Abstract] OR "World Cup" [Title/Abstract] OR
 "World Championship*" [Title/Abstract] OR marathon* [Title/Abstract] OR "Tour de
 France" [Title/Abstract] OR "Grand Slam" [Title/Abstract] OR "Super Bowl" [Title/Abstract] OR
 "Cricket World Cup" [Title/Abstract] OR "Formula One" [Title/Abstract] OR "Formula 1" [Title/
 Abstract] OR Games [Title/Abstract] OR "Commonwealth Games" [Title/Abstract] OR "Pan
 American Games" [Title/Abstract] OR "Pan Am Games" [Title/Abstract] OR "African Games" [Title/
 Abstract] OR "All-Africa Games" [Title/Abstract] OR "Pan African Games" [Title/Abstract] OR "Pan-
 Asian Games" [Title/Abstract] OR "Asian Games" [Title/Abstract] OR "European Games" [Title/
 Abstract] OR "public event*" [Title/Abstract] OR "religious event*" [Title/Abstract] OR "religious
 gathering*" [Title/Abstract] OR "semi-outdoor event*" [Title/Abstract] OR "athletic event*" [Title/
 Abstract] OR amusement [Title/Abstract] OR "sport event*" [Title/Abstract] OR "sporting
 event*" [Title/Abstract] OR pilgrimage* [Title/Abstract] OR concert* [Title/Abstract] OR gig [Title/
 Abstract] OR gigs [Title/Abstract] OR rockfest [Title/Abstract] OR "cultural event*" [Title/Abstract]
 OR "endurance event*" [Title/Abstract] OR fair* [Title/Abstract] OR festival* [Title/Abstract] OR
 festivit* [Title/Abstract] OR recreation [Title/Abstract] OR "large scale event*" [Title/Abstract] OR
 "large-scale event*" [Title/Abstract] OR "marathon event*" [Title/Abstract] OR "mass
 event*" [Title/Abstract] OR "mass gathering*" [Title/Abstract] OR "mass participation
 event*" [Title/Abstract] OR "mega event*" [Title/Abstract] OR "mega-event*" [Title/Abstract] OR
 "mega sporting event*" [Title/Abstract] OR "mega-sporting event*" [Title/Abstract] OR "mega
 sport event*" [Title/Abstract] OR "mega-sport event*" [Title/Abstract] OR "music festival*" [Title/
 Abstract] OR "outdoor event*" [Title/Abstract] OR parade* [Title/Abstract] OR
 competition* [Title/Abstract] OR fiesta* [Title/Abstract] OR jubilee [Title/Abstract] OR
 ceremon* [Title/Abstract] OR procession* [Title/Abstract] OR spectacle* [Title/Abstract] OR
 exhibition* [Title/Abstract] OR fanfare* [Title/Abstract]) AND ("tailored communication" [Title/
 Abstract] OR "tailored messaging" [Title/Abstract] OR "targeted communication" [Title/Abstract]
 OR "targeted support" [Title/Abstract] OR "visual communication" [Title/Abstract] OR "risk
 communication" [Title/Abstract] OR "risk messaging" [Title/Abstract] OR "safety
 communication" [Title/Abstract] OR "symbol-based communication" [Title/Abstract] OR
 "behaviour change communication" [Title/Abstract] OR "behavioural prompt*" [Title/Abstract]
 OR "health communication" [Title/Abstract] OR "health education" [Title/Abstract] OR "digital

health intervention*[Title/Abstract] OR "health messaging"[Title/Abstract] OR "heat risk communication"[Title/Abstract] OR "heat safety advice"[Title/Abstract] OR "heat-health communication"[Title/Abstract] OR "linguistically tailored communication"[Title/Abstract] OR "medical assistance awareness"[Title/Abstract] OR "multi language"[Title/Abstract] OR "multi-language"[Title/Abstract] OR multilingual[Title/Abstract] OR "plain language"[Title/Abstract] OR "preventive guid*[Title/Abstract] OR "protective behaviour*[Title/Abstract] OR "public health advisory*[Title/Abstract] OR "public health messaging"[Title/Abstract] OR "vulnerability identification"[Title/Abstract] OR "risk screening"[Title/Abstract] OR "risk stratification"[Title/Abstract] OR "special needs identification"[Title/Abstract] OR "health assessment"[Title/Abstract] OR "culturally appropriate"[Title/Abstract] OR "culturally sensitive"[Title/Abstract] OR "culturally tailored"[Title/Abstract] OR "easy-to-read"[Title/Abstract] OR "health questionnaire*[Title/Abstract] OR "health screening"[Title/Abstract] OR "language accessible"[Title/Abstract] OR "language-accessible"[Title/Abstract] OR "low literacy"[Title/Abstract] OR "low-literacy"[Title/Abstract] OR "medical screening"[Title/Abstract] OR mHealth[Title/Abstract] OR "pre-event screening"[Title/Abstract] OR "pre-registration data"[Title/Abstract] OR "pre-registration screening"[Title/Abstract] OR "priority access"[Title/Abstract] OR "registration screening"[Title/Abstract] OR "body temperature sensor*[Title/Abstract] OR "camera-based monitoring"[Title/Abstract] OR "computer vision"[Title/Abstract] OR "core temperature sensor*[Title/Abstract] OR "environmental sensor*[Title/Abstract] OR "heart rate sensor*[Title/Abstract] OR "heart rate monitoring"[Title/Abstract] OR "infrared camera*[Title/Abstract] OR "thermal camera*[Title/Abstract] OR "skin temperature sensor*[Title/Abstract] OR "temperature sensor*[Title/Abstract] OR "wearable device*[Title/Abstract] OR "wearable sensor*[Title/Abstract] OR "biometric monitoring"[Title/Abstract] OR "wearable alert*[Title/Abstract] OR "wearable device*[Title/Abstract] OR "wearable sensor*[Title/Abstract] OR "heat strain monitor*[Title/Abstract] OR "thermal strain monitor*[Title/Abstract] OR "vibration alert*[Title/Abstract] OR "visual alert*[Title/Abstract] OR "smart watch*[Title/Abstract] OR "smart wearable*[Title/Abstract] OR smartwatch*[Title/Abstract] OR "sound alert*[Title/Abstract] OR "biometric monitoring"[Title/Abstract] OR "heat alert*[Title/Abstract] OR "heat warning*[Title/Abstract] OR "hydration advice"[Title/Abstract] OR "physiological monitor*[Title/Abstract] OR "real time alert*[Title/Abstract] OR "real-time alert*[Title/Abstract]) AND ("heat illness*[Title/Abstract] OR "heat injur*[Title/Abstract] OR "heat related illness*[Title/Abstract] OR "heat-related illness*[Title/Abstract] OR "heat stress disorder*[Title/Abstract] OR "heat stress disorder*[Title/Abstract] OR miliaria[Title/Abstract] OR "heat rash*[Title/Abstract] OR dermatoses[Title/Abstract] OR "heat fatigue"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heat syncope"[Title/Abstract] OR collapse[Title/Abstract] OR fainting[Title/Abstract] OR dizziness[Title/Abstract] OR "heat cramps"[Title/Abstract] OR "heat oedema"[Title/Abstract] OR "heat edema"[Title/Abstract] OR "heat exhaustion"[Title/Abstract] OR "heat stroke"[Title/Abstract] OR "exertional heat stroke"[Title/Abstract] OR "classical heat stroke"[Title/Abstract] OR disorientation[Title/Abstract] OR aggressiv*[Title/Abstract] OR seizure*[Title/Abstract] OR coma[Title/Abstract] OR "organ damage"[Title/Abstract] OR "tissue damage"[Title/Abstract] OR coagulopathy[Title/Abstract] OR "systemic inflammatory response syndrome"[Title/Abstract] OR "heat-induced dyslipidaemia"[Title/Abstract] OR "fluid imbalance*[Title/Abstract] OR "electrolyte imbalance*[Title/Abstract] OR hypohydration[Title/Abstract] OR dehydration[Title/Abstract] OR "kidney disease*[Title/Abstract] OR "kidney disfunction"[Title/Abstract] OR "kidney injur*[Title/Abstract] OR "acute kidney injur*[Title/Abstract] OR "chronic kidney injur*[Title/Abstract] OR "kidney stones"[Title/Abstract] OR death*[Title/Abstract] OR attitude*[Title/Abstract] OR awareness[Title/Abstract] OR compliance[Title/Abstract] OR behavio*[Title/Abstract]

Abstract] OR knowledge[Title/Abstract] OR "protective behavio*" [Title/Abstract] OR perception* [Title/Abstract] OR "risk perception" [Title/Abstract] OR "help-seeking behavio*" [Title/Abstract] OR acceptability[Title/Abstract] OR adherence[Title/Abstract] OR vulnerab* [Title/Abstract] OR screening[Title/Abstract] OR "alert perform*" [Title/Abstract] OR "missed event*" [Title/Abstract] OR "implementation outcome*" [Title/Abstract] OR "intervention fidelity" [Title/Abstract] OR feasibility[Title/Abstract] OR "response pathway*" [Title/Abstract] OR "response time" [Title/Abstract] OR uptake[Title/Abstract] OR "vulnerable group outcome*" [Title/Abstract] OR "false alarm*" [Title/Abstract] OR "false positive*" [Title/Abstract] OR "false negative*" [Title/Abstract] OR heat[Title/Abstract] OR "heat stress" [Title/Abstract] OR "heat exposure" [Title/Abstract] OR "heat exposure condition*" [Title/Abstract] OR "environmental heat" [Title/Abstract] OR "environmental temperature" [Title/Abstract] OR "hot condition*" [Title/Abstract] OR "excess heat" [Title/Abstract] OR "thermal load" [Title/Abstract] OR "thermal stress" [Title/Abstract] OR "thermal strain" [Title/Abstract] OR "hot environment*" [Title/Abstract] OR "high temperature environment*" [Title/Abstract] OR "high-temperature environment*" [Title/Abstract] OR "hot climatic condition*" [Title/Abstract] OR "extreme temperature" [Title/Abstract] OR "high heat" [Title/Abstract] OR "high-heat" [Title/Abstract] OR "extreme heat" [Title/Abstract] OR temperature* [Title/Abstract] OR "high temperature*" [Title/Abstract] OR "Wet Bulb Globe Temperature" [Title/Abstract] OR WBGT[Title/Abstract] OR "heat index" [Title/Abstract] OR "heat stress index" [Title/Abstract] OR "environmental heat index" [Title/Abstract] OR "thermal stress index" [Title/Abstract] OR "Universal Thermal Climate Index" [Title/Abstract] OR UTCI[Title/Abstract] OR humid* [Title/Abstract] OR "relative humidity" [Title/Abstract] OR "humid heat exposure" [Title/Abstract])

Annex 3

Data extraction

Annex 3.1 Summary of data extraction table systematic review 1

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Seiler, 2025	Spectators	Mass gathering	Medical care included on-site nurse practitioners, on-site treatment, hospitalizations and minimal interventions.	Outcomes for the 147 total cases included 28 (19%) requiring minimal intervention (near-syncope, feeling overheated, nausea and vomiting, isolated minor trauma, headache); 89 (60.5%) treated and released on-site (syncope, weakness and dizziness, heat-related illness/dehydration, mild allergic reactions, cellulitis or other wound infections, nausea and vomiting, minor trauma with lacerations); 15 (10.2%) transported to hospital (severe heat-related illness, intoxication without decision-making capacity, seizure-like activity, chest pain and cardiac complaints, stroke-like symptoms, altered mental status, generalized abdominal pain); and 16 (10.8%) refusing further care or transport (cardiac-related complaints, isolated trauma, syncope, heat-related complaints, pregnancy-related complaints).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Samarkandi, 2025	Pilgrims	Religious	Preventive measures implemented by the Saudi Arabian Ministry of Health included water mist sprays in ritual areas; planting trees and creating green spaces at holy sites; providing free water, umbrellas and temporary air-conditioned tent housing; and operating free health services and seasonal health camps with cooling units to expedite cooling after intense heat exposure.	Findings indicated that 40.1% of pilgrims requested urgent health assistance with severe symptoms; there was a high prevalence of risk-taking behaviours related to heat and care-seeking; and 36.6% of participants were classified as engaging in high-risk behaviour.
Rahim, 2025	Visitors	International exhibition	Interventions included multichannel health promotion (hydration, shade, and early signs of heat exhaustion/heatstroke); two strategically located medical tents with on-site health care personnel and consultations; hospitalizations; psychosocial and mental health support (social workers, psychologists, psychiatrists, counsellors); and 151 public health personnel for communicable disease surveillance, vector-borne disease control and environmental health assessments.	Recorded outcomes included 102 cases of acute gastroenteritis (AGE), 715 cases of upper respiratory tract infection (URTI) and 5 cases of COVID-19; no disease outbreaks were detected; and one hiker was reported missing.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Mercalli, 2025	Spectators; staff	Sporting	Medical resources included a field hospital with specific zones (shock, treatment, working, VIP/ isolation and physical therapy rooms); multiple first aid stations and points; mobile on-field medical response teams for rapid intervention; sports medicine support with fast-tracking; on-field resources including patrol crews and transport vehicles; and a multidisciplinary team of physicians, nurses and technicians.	Outcomes for 152 total spectators included 121 discharged, 17 centralized to the emergency department, 5 centralized to a non-urgent clinic, 4 refusing treatment or centralization and 5 leaving before being seen; among spectators there were 52 trauma cases (23 strain/contusive, 11 falls, 5 wounds, 2 burns, 3 sport-specific and 8 other traumatic injuries); 22 cardiovascular cases (14 syncope, 6 chest pain and 2 other); 15 cases of heat-induced exhaustion; 17 insect bites; 11 gastroenterological cases (2 abdominal pain and 9 vomiting and diarrhoea); 7 dermatological cases (5 dermatitis and 2 exercise-induced vasculitis); 4 infectious cases (3 COVID-19 and 1 other); 5 neurological cases; 3 respiratory cases; 1 panic attack; 3 dysglycaemia cases; 3 cases of alcohol abuse; 2 cases of home drug administration; and 7 miscellaneous cases. (continues)

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
				(continued)
				Staff outcomes included 52 discharged, 6 centralized to the emergency department, 2 centralized to a non-urgent clinic, and 1 refusing treatment or centralization; among the staff there were 22 trauma cases (7 strain/contusive, 5 falls, 2 wounds, 5 burns and 3 other traumatic injuries); 8 cardiovascular cases (4 syncope, 1 chest pain and 3 other); 8 cases of heat-induced exhaustion; 5 insect bites; 5 gastroenterological cases (2 abdominal pain and 3 vomiting and diarrhoea); 3 dermatological cases (2 dermatitis and 1 exercise-induced vasculitis); 3 infectious cases; 2 neurological cases; 1 respiratory case; 2 panic attacks and 2 miscellaneous cases.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Habrat, 2025	Spectators	Series of music festivals	Medical resources included a main temporary treatment facility, first aid stations, mobile medical teams, pre-positioned ambulances and multidisciplinary teams (emergency medical technicians, paramedics, emergency nurses and physicians). Interventions for presumed psychostimulant toxicity focused on initial sedation (intramuscular ketamine or midazolam) and confirming hyperthermia; for patients with a pre-hospital rectal temperature >40 °C, protocols per event guidelines included advanced airway placement, intravenous hydration and closely monitored rapid cooling via submersion in pre-positioned ice-water tanks. Escalation protocols for cardiac arrest during cooling necessitated immediate removal from the submersion tank, physician-led CPR and acute resuscitation prior to transport to the closest hospital.	Outcomes included 123 patients transported to surrounding hospitals, of whom 21 were diagnosed with hyperthermia.
Collins, 2024	Spectators	Sport	Interventions included providing medical treatment and facilitating transfer to a hospital.	Heat-related complaints were the most common, accounting for 42% of cases during the game on 3 September (8.4 per 10 000 spectators), 63% during the game on 10 September (4.2 per 10 000) and 60% during the game on 29 October (1.7 per 10 000); overall, 40–60% of all cases were heat-related illness, with most occurring on the stadium's hotter side.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Maleczek, 2022	Spectators	Music	On-site medical services provided by the Austrian Red Cross included free drinking water; eight first aid posts, each staffed with four emergency medical technicians; and one main first aid post equipped with two resuscitation pods and eight intermediate care pods to monitor patients and provide advanced cardiac and trauma life support.	Over 7 years, 13 759 patients were treated and 612 transported to hospital; the most common reasons for transfer included pain (8910), exanthema (178), follow-up treatment (1384), unknown (1001), altered mental state (908), dizziness (613), diarrhoea (443), dyspnoea (100), psychiatric (96), fever (74) and atraumatic bleeding (73); pain etiologies included trauma (6241 of pain; 3587 blunt, 1289 unknown mechanism, 1264 penetrating), insect bites (734), unknown origin (728), ear, nose, throat (269) and burns (214); mean presentation rate was 12.01 per 1000 and transport rate was 0.57 per 1000; intoxication was involved in 746 cases: 86% alcohol-related and 14% (104 cases) recreational drugs.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Imbriaco, 2022	Spectators	Sport	Medical assistance involved 68 operators per match, including 10 basic life support teams of four volunteer rescuers in the stands (equipped with scoop stretchers, automated external defibrillators, and emergency backpacks); two teams of four operators at the stand bases (equipped with wheeled stretchers to transport patients to medical posts); two ambulances located at the sides of the stadium, each staffed with one emergency nurse and one emergency physician (equipped with emergency and resuscitation equipment); and pitch intervention personnel comprising one team (one emergency nurse and three volunteer rescuers) alongside one advanced life support team (one emergency physician, one emergency nurse and one rescuer).	Daily match-specific outcomes in June 2019 included 4 patients assessed during the 16 June Italy–Spain match (1 trauma (25%) and 3 non-traumatic (75%)); 3 patients during the 19 June Italy–Poland match (1 trauma (33%) and 2 non-traumatic (67%)); 1 patient during the 22 June Spain–Poland match (0 trauma and 1 non-traumatic (100%)); and 23 patients during the 27 June Germany–Romania match (2 trauma (9%) and 21 non-traumatic (91%)).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Almuzaini, 2021	Pilgrims	Religious	Heat exhaustion management included moving patients to cooler areas; supine positioning with elevated legs and hips; loosening clothes; oral hydration; intravenous fluids; cooling and facility transfer; and considering alternative diagnoses. Pre-hospital interventions for heatstroke involved body substance isolation; administering medications; taking full pre-hospital reports; recognizing heatstroke; assessing responsiveness and vital signs; stabilizing airway, breathing and circulation; immediate on-scene cooling; and immediate transfer to a heatstroke unit with continuous cooling. Heatstroke in-hospital management included using personal protective equipment; withholding antipyretics; taking full pre-hospital reports; confirming diagnosis via rectal thermometer; continuous cooling and monitoring (maintaining skin temperature > 30 °C, and discontinuing cooling once rectal temperature reached 39 °C); stabilizing airway, breathing and circulation; fluid volume expansion; administering intravenous furosemide, mannitol, sodium bicarbonate and benzodiazepines (for seizures/shivering); managing electrolytes and treating hyperkalaemia; and supportive therapy for multiple organ dysfunction.	Outcomes for a total of 98 patients included 48 (49%) diagnosed with heat exhaustion and 50 (51%) with heatstroke; specific interventions for 49 patients involved moving to a cooler location, supine positioning with elevated legs and hips, starting oral hydration, loosening clothing and cooling prior to facility transfer; 9 patients received intravenous fluids for nausea; and 49 patients were managed using body substance isolation precautions and pre-hospital medication.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Nayar, 2020	Pilgrims	Religious	Health service providers available at the centres included qualified medical (modern medicine) doctors in most cases, while a few people consulted Ayurvedic doctors, nurses or pharmacists.	Outcomes and health indicators for the Sabarimala pilgrimage included pre-ascent hypertension (n=291; 23.1%), diabetes mellitus (n=336; 26.7%), lung disease (n=17; 1.4%) and heart disease (n=12; 1%), with 19.1% (n=240) having consulted a doctor pre-travel and a similar subset monitoring blood pressure (n=215; 19.1%) or blood glucose (n=212; 16.8%); health problems during the climb affected 43.4% of pilgrims (n=546), specifically leg pain (n=517; 41.1%), other joint or muscle pain (n=308; 24.5%), breathlessness (n=117; 9.3%), headache (n=48; 3.8%), chest pain (n=21; 1.7%) and dizziness (n=11; 0.9%); post-pilgrimage issues reported by 12.8% (n=161) included leg pain (n=117; 72.7%), joint or muscle pain (n=105; 65.2%), cough (n=39; 24.2%), headache (n=34; 21.1%), breathlessness (n=22; 13.7%), chest pain (n=19; 11.8%), fever (n=19; 11.8%), vomiting (n=11; 6.8%), abdominal pain (n=4; 2.5%), dizziness (n=2; 1.2%) and diarrhoea (n=1; 0.6%); (continues)

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
				(continued) management of health complaints for 161 individuals was predominantly informal, with 55.3% (n=89) doing nothing, 18.6% (n=30) self-medicating, 14.9% (n=24) using local pharmacies, 7.5% (n=12) receiving medicine from fellow pilgrims and only 3.7% (n=6) visiting a government facility; secondary data analysis identified respiratory infections (38.5%) and gastrointestinal diseases (21.5%) as the most common presentations, with 1 in 10 presenting with cardiovascular disease, 1 in 1000 with myocardial infarction and 1 in 5 requiring surgical care for foot injuries. Mass-gathering indicators from 2014–2017 included an average patient presentation rate of 4999.6 and a referral to hospital rate of 19 per 100 000, with annual mortality ranging from 18.5 to 23.3 per 100 000 and deaths from coronary artery heart disease declining from 97.6% to 85.1%.
Yezli, 2019	Pilgrims	Religious	Preventive measures included improvements in Hajj infrastructure and services; distribution of free umbrellas and water; and health education campaigns about heat-related illness, delivering messages to pilgrims both before and during the Hajj in Saudi Arabia.	Not reported

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Ranse, 2019	Spectators	Music	On-site medical resources included a first aid post; an in-event health service tent staffed by volunteer health professionals (an intensive care registrar, a resident medical registrar, two emergency nurses and one paramedic); and a government ambulance staffed by two paid paramedics. Interventions and treatments included first-line medications and simple interventions (note: no on-site imaging or pathology diagnostics); intravenous fluids (0.9% sodium chloride); antiemetics (ondansetron); and additional emergency medications and interventions prior to transport to hospital, including midazolam, naloxone, and airway management (endotracheal intubation and nasopharyngeal/oropharyngeal airway adjuncts).	Outcomes for a total of 197 cases included 173 (87.8%) who received in-event first aid care only, with the most prevalent presentations being headaches (n=94; 54.3%), superficial lacerations (n=13), and substance or alcohol intoxication (n=12); 24 cases (12.2%) required in-event health professional care, which primarily addressed headaches (n=3), fractures (n=2), and substance or alcohol intoxication (n=12); of those seen by health professionals (n=24), 15 received care and returned to the event following administration of intravenous fluids (n=13) and/or antiemetics (n=11); 7 were referred to ambulance paramedic care and transported to hospital, some requiring endotracheal intubation (n=1) and airway adjuncts (n=3) prior to transport; and 2 patients were discharged into the care of the police.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Khan, 2018	Pilgrims	Religious	The 2016 Indian Medical Mission (August–October; Mecca, Medina, Jeddah) comprised 144 doctors, 50 specialists, 146 paramedics and 74 ancillary staff providing tiered health care with referral and evacuation capabilities. Components included 22 static primary-care clinics covering 400 buildings with capability for onward referral; 35 tent clinics covering 5000 tents in Mina/Arafat and 1.4 million unsheltered Muzdalifah pilgrims; one mobile referral tent-clinic catering to 35 satellite clinics; mobile task forces (1 doctor and 2 paramedics/shift) covering large gatherings, with onward referral; secondary-care hospitals (two 40-bed in Mecca, one 14-bed in Medina) providing 11 specialties; and tertiary-care transfer coordination with 30 Saudi hospitals.	Outcomes for 2016 included 394 013 outpatient visits (primarily to static clinics), 930 secondary-care referrals (with 585 hospitalizations), 523 tertiary-care referrals (with 495 hospitalizations/institutionalizations), a crude mortality rate of 11.99 per 10 000 (163 deaths), and 83 patients with heat illnesses were treated in tent clinics (48 heat-hyperpyrexia and 35 heat exhaustion); across the 2014–2016 period, annual primary-care morbidity (ranging from 394 013 to 419 508 cases) was consistently dominated by infectious diseases (53–57%) and orthopaedic/musculoskeletal diseases (23–25%); secondary-care hospitalizations (585 to 681 annually) were primarily for gastrointestinal (26–29%) and respiratory diseases (16–21%); tertiary-care referrals (495 to 636 annually) were largely driven by cardiovascular disease (17–27%) and orthopaedics/trauma (16–26%); and total annual mortality across the three years (149 in 2014; 313 in 2015; 163 in 2016) was overwhelmingly caused by cardiorespiratory arrest (102 to 164 deaths annually), with a notable spike in unnatural incidents occurring in 2015 (103 deaths).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
DeMott, 2018	Spectators	Music; sport	Three large events (Lollapalooza, Spring Awakening and Pitchfork) accounted for most (n = 112, 54%) of the patients seen in the emergency department (of a tertiary academic medical centre) where this retrospective medical record review took place.	Outcomes for a total of 209 patients, of whom 180 were analysed specifically from concerts, included 158 environmental presentations (including weather-related complaints (e.g. sunburn) and substance-related complaints (e.g. alcohol and illicit substance intoxication), 112 illnesses, 39 mental health cases and 32 injuries; arrivals at the emergency department comprised 168 patients via ambulance and 12 walk-ins; and emergency department disposition resulted in 161 discharges, 6 admissions to the intensive care unit, 5 to the general medical floor, 1 for general medical floor observation, 4 leaving against medical advice and 3 who absconded.
Abdelmoety, 2018	Pilgrims	Religious	Preparedness measures by the Saudi Ministry of Health and Hajj Committees included providing equipment, facilities and trained staff to hospitals in Mina, El Mashaeer and Makkah. Participant education and prevention strategies during Hajj included instructions to stay in shelters, use sunblock, maintain adequate water intake, utilize flexible timing (performing rites at night if possible) and practise handwashing.	Outcomes for 267 patients with HRI enrolled in the study included 80 patients with heatstroke (29%) and 187 with heat exhaustion (67.75%), with an overall median length of stay of 2 hours (IQR 1–12; maximum 57 hours); heatstroke outcomes included 84.3% improved or discharged, 5.7% admitted to critical care units and 7.1% deaths; heat exhaustion outcomes included 162 (94.7%) improved or discharged, 7 (4.1%) discharged against medical advice, 2 (1.2%) admitted to critical care and 0% deaths; and clinical signs and symptoms for heatstroke (n = 80) versus heat exhaustion (n = 187), (continues)

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
				(continued) respectively, were altered mental status (50 (62.5%) versus 7 (4.0%)), tachycardia (37 (46.3%) versus 7 (4.0%)), tachypnoea (29 (36.3%) versus 4 (2.1%)), hypotension (19 (23.8%) versus 3 (1.6%)), convulsions (11 (13.8%) versus 1 (0.5%)), diarrhoea (5 (6.3%) versus 1 (0.5%)), dizziness (1 (1.2%) versus 40 (21.4%)), vomiting (0 versus 20 (10.7%)), headache (0 versus 14 (7.5%)), irritability (1 (1.2%) versus 12 (6.4%)), nausea (0 versus 6 (3.2%)) and postural hypotension (0 versus 4 (2.1%)).
Ho, 2014	Spectators	Sport	Medical resources included an on-site spectator medical team providing triage, treatment, observation and evacuation; a command centre supporting 8 advanced medical posts capable of advanced cardiac life support and 18 first aid posts; automated external defibrillators at selected posts; standby transport buggies and ambulances; a multidisciplinary track medical team located along the circuit with on-site radiology equipment; and escalation protocols to transfer ill patients to the track medical centre rather than a hospital.	Outcomes and health indicators included daily treated patient volumes ranging from 90 to 254, with a daily average of 2.8 ambulance transfers; patient presentations peaked between 17:00 and 22:00 (66.6%), corresponding to motor racing hours; primary presentations consisted of musculoskeletal conditions (59%; including blisters, lacerations, abrasions, sprains and strains) and heat-related illnesses (19%; including dehydration, headache, sunburn, faintness and syncope); and overall mass-gathering indicators showed an average patient presentation rate of 2.17 per 1000 attendees and an average transport to hospital rate of 0.033 per 1000 attendees.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Chia, 2011	Volunteers	Sport	Medical resources included 33 medical rooms and 86 medical aid stations at competition venues, equipped for urgent trauma, cardiac and minor care; 55 first-aid posts for spectators; standby ambulances at each venue and a central location with planned evacuation routes; designated hospital emergency departments briefed on venue-specific sports; and pandemic and infectious disease control measures including venue screening and temperature measurements.	Outcomes of medical encounters involving non-athletes represented 40.9% of the total; the longest hospitalization (29 days) involved a non-athlete (Games official) treated for a dissecting aneurysm; and workforce personnel accounted for 20.9% of all hospital referrals, compared to 51.8% for athletes.
Yazawa, 2007	Visitors	Culture	Interventions involved a coordinated emergency medical care system integrating medical teams, emergency medical services, police, related agencies and local hospitals; clinician-staffed first-aid tents and stations with standby ambulances; two strategically positioned first-aid stations at the Lower Shrine, each staffed by two doctors, three nurses, one emergency crew and one medical technician, and equipped with a first-aid kit, ventilator, backboard and automated external defibrillator; three standby ambulances and a mass-casualty disaster bus; and approximately 50 Red Cross volunteers alongside medical students assisting with patient transport and emergencies.	Outcomes across the festivals were as follows: Upper Shrine Yamadashi, 19 patients (1 severe pelvic fracture) and daily cases/transport over 3 days of 0/0, 11/9 and 8/4 (weather shifted from rain to sun to snow with temperatures of 1.0–3.6 °C); the Upper Shrine Satobiki, 25 patients and daily cases/transport of 3/0, 12/2 and 10/2 (weather consistently cloudy); the Lower Shrine Yamadashi, 146 patients (92 trauma (63%), 54 medical (37%)) and daily cases/transport of 37/9 (sunny), 59/18 (cloudy), and 50/9 including 1 life-threatening (cloudy) at temperatures of 17–21 °C; and the Lower Shrine Satobiki, 47 patients (3 injuries, 9 heat-related, 2 alcohol-related, 3 other) and daily cases/transport of 30/6 (fair, 23 °C), 7/3 (rain, 14 °C), and 10/1 (rain).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Olapade-Olaopa, 2006	Spectators	Sport	Interventions and resources included pre-event training workshops, an operational plan and daily debriefings; 10 pitch-side on-site medical centres staffed with a doctor, nurse, physiotherapist and f students trained in first-aid; secondary medical centres and a tertiary medical centre; 8 well-equipped ambulances for transfers; dedicated teams at referral centres to avoid delays; and a subcommittee to restock and supplement disposables and drugs.	Outcomes for 494 total visits (486 athletes/officials; 8 spectators with minor ceremony injuries) resulted in 90% managed on-site, 5% referred to secondary care, 3% to tertiary care, and 0 deaths; injury grades comprised 278 minor (56%), 182 intermediate (37%), 15 major (3%) and 19 unclassified (4%).
Lukins, 2004	Spectators	Music	Medical resources and protocols included 5 on-site first-aid posts at the crowd perimeter and a fixed medical facility in an aircraft hangar with pre-installed air conditioning for a cooled environment; the fixed facility comprised 6 first-aid posts, a 186-patient-capacity main field hospital staffed by emergency physicians and nurses and a medical rehydration unit; the rehydration unit had a 48-stretcher capacity (with surge capacity to 64 stretchers) and was staffed by emergency medical services paramedics with on-site medical direction by physicians; staff preparation included a paramedic training session on features of heat-related illness and directives for oral and parenteral fluid therapy; and a screening and triage system where paramedics screened and directed patients to first aid, the main field hospital or the medical rehydration unit.	Outcomes included a total of 1870 medical presentations (42 per 10 000; 1205 records available) with 465 treated at the main field hospital; heat-related illness treated in the medical rehydration unit accounted for 143 cases (3 per 10 000), where treatments included parenteral/oral fluids for 44 patients (31%; mean intravenous volume 1017 mL (95% confidence interval 867–1158)), oral fluids only for the remainder, acetaminophen for 43 (30%), and dimenhydrinate for 17 (12%); and medical rehydration unit dispositions included 107 discharged (75%), 17 transferred to the main field hospital (12%), 4 leaving against medical advice (3%), 2 transferred off-site (1%) and 13 with incomplete records (9%).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Griffith, 2004	Spectators	Airshow	Medical resources included first aid tents providing medical care staffed by senior emergency medicine residents or emergency medicine attendings.	Outcomes were recorded for a total of 251 patients; transport data were available for only 130 individuals, with no absolute hospital transport counts reported.
Feldman, 2004	Spectators	Music	Interventions and resources included a three-tier medical care system comprising ambulances/first-aid posts, a rehydration unit and a field hospital; a hangar-based field hospital staffed by a multidisciplinary volunteer team (physicians, nurses, allied health and support staff); an adjacent 48-bed medical rehydration unit staffed by paramedics with medical oversight; five peripheral first-aid tents; a fenced central access corridor for crew; a temporary helipad; 270 emergency medical technicians, all-terrain vehicle and bicycle teams together with 25 ambulances; tactical emergency medical services and paramedic teams trained in chemical, biological, radiological and nuclear medicine on standby; additional support from first-aid volunteers and firefighters; and pre-event shift briefings covering site logistics, treatment-and-release for simple complaints and rehydration therapy.	Outcomes included 1870 presentations (42 per 10 000) with 665 unrecorded minor requests and 1205 recorded cases; of the recorded cases, 795 (66%) received initial care in a first-aid tent (356 (29.5%) released; 385 (48%) transferred to field hospital/rehydration unit), 143 (11.9%) were treated at the rehydration unit, 453 (37.6%) at the field hospital, 5 were transferred directly off-site, 12 left against medical advice, and disposition data were lacking for 37; the main complaints were headache (321, 27%), dehydration/heat-related illness (148, 12%), trauma (123, 10.2%), nausea/vomiting (91, 7.6%), shortness of breath (79, 6.5%), syncope (46, 3.8%), alcohol/drug intoxication (30; 2.5%), other (201, 16%), and unspecified (166, 13.8%); total number of hospital transports was 24 (0.5 per 10 000; 0 aeromedical) primarily for severe intoxication/decreased awareness (4; 17%), shortness of breath (4; 17%), cardiac symptoms (3; 13%) and unspecified reasons (5); and there were no deaths, cardiac arrests or penetrating injuries.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Grange, 2003	Spectators	Sport	Medical resources included approximately 100 medical team personnel (physicians, nurses, paramedics, dispatchers) providing care across various units; up to nine daytime first aid stations staffed by nurses and paramedics, with two of these stations staffed with emergency physicians and equipment for advanced medical interventions (including advanced airway management, defibrillation/cardioversion, central line insertion, suturing, splinting and medications); a nighttime “Infield Care Center” staffed by an emergency physician, nurse and paramedics; four roving advanced life support mini-ambulances; nine roving golf cart teams; and a dedicated, medically configured helicopter with a flight crew.	Outcomes were available for a total of 485 patients who included 331 spectators (68%) and 121 track staff, vendors and officials (25%); the main complaints comprised 140 soft-tissue injuries (29%), 130 headaches (27%), 93 miscellaneous (19%), 36 orthopaedic (7%), 26 eye problems (5%), 19 gastrointestinal (4%), 13 heat-related illnesses (3%), 10 burns (2%), 9 respiratory (2%), 4 cardiac (1%), 2 allergic reactions (0%), 2 intoxications (0%) and 1 major trauma (0%).
Seraj, 1991	Pilgrims	Religious	Medical interventions and monitoring included the use of body surface cooling; intravenous lines, blood sampling and oxygen therapy; continuous 4-channel temperature monitoring (three skin surface temperatures and rectal temperature) alongside pulse, blood pressure and respiratory rate recorded every 5 minutes; and targeted cooling protocols that were stopped when the patient's core temperature dropped to 39 °C.	Outcomes and clinical metrics for 34 treated patients included 22 with a central venous pressure of +3 cmH ₂ O or above (64.7%), of which 6 had a central venous pressure of +10 cmH ₂ O or more (range 10–26 cmH ₂ O) at the start of intravenous therapy, and 12 with a central venous pressure of zero or below (35.3%); fluid resuscitation required a mean crystalloid infusion of 1060 mL (range 500–2500 mL) over an average cooling time of 1 hour (range 20–96 min), with only 3 patients needing more than 2 litres of fluid during cooling.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Gustafson, 1987	Visitors	Mass gathering	Medical resources and transportation included a 10-bed infirmary staffed by three nurses per shift, supported by emergency medical technicians and communications personnel; and two ambulances, four mini-ambulances and two golf carts. Preventive measures included advising bands to wear lighter uniforms and avoid long periods of standing before marching; local radio advisories for visitors to wear summer clothing; painting black-top walkways white to minimize heat retention; and installing additional drinking fountains.	Outcomes included a total of 24 747 infirmary visits and mini-ambulance calls (23 per 10 000 visits), with 911 patients transported to nearby hospitals; presentation rates per 10 000 visits included 5 for headaches, 5 for foot blisters, 3 for gastrointestinal complaints (abdominal pain, nausea, vomiting), 2 for cuts and falls, 0.4 for chest pain (394 total cases), 0.2 for febrile illnesses (particularly in children), 0.08 for diabetic emergencies and 0.06 for seizures; and critical events included 12 patients with cardiac arrest, 10 of which were successfully resuscitated on-site.
Baker, 1986	Spectators	Sport	Medical resources included medical aid stations staffed by volunteer physicians and registered nurses; at least one physician assigned to each spectator medical station at events with more than 3000 spectators; teams of two first aiders available per 8000 spectators, supervised by a first aid coordinator; basic life support ambulances at each event site; air ambulance helicopter services at selected remote sites; and coordination with 17 local acute care hospitals for patient transport.	Outcomes were categorized into 772 trauma cases (43.3%) and 1011 nontrauma cases (56.7%); trauma presentations comprised minor musculoskeletal (293; 16.4%), minor dermal (150; 8.4%), open wounds (125; 7.0%), significant musculoskeletal (73; 4.1%), insect bites (68; 3.8%), foreign bodies (27; 1.5%), eye injuries (19; 1.1%), closed-head injuries (11; 0.6%) and other trauma (6; 0.3%); nontrauma presentations comprised heat-related illness (213; 11.9%), minor gastrointestinal (140; 7.9%), minor infections (129; 7.2%), anxiety, hyperventilation or dizziness (65; 3.6%), dermatitis (51; 2.9%), eye disease (45; 2.5%), headache (39; 2.2%), cardiac problems (35; 2.0%), abdominal pain/acute abdomen (30; 1.7%), syncope (23; 1.3%), dehydration (19; 1.1%), asthma (15; 0.8%), hypertension (13; 0.7%), (continues)

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
				(continued)
				hypoglycaemia or diabetes (11; 0.6%), epistaxis (10; 0.6%), seizure, cerebrovascular accident, transient ischaemic attack (9; 0.5%), alcohol or drug ingestion (8; 0.4%), pregnancy or vaginal haemorrhage (6; 0.3%), gastrointestinal bleed (4; 0.2%), kidney stones (2; 0.1%), and other nontrauma (144; 8.1%).
Pons, 1980	Spectators	Sport	Medical resources included multiple stadium first aid rooms, with three functioning as first aid stations (two staffed by paramedics and physicians); an overall staff of 12 paramedics and 7 physicians; emergency transport via two stationed ambulances and two stretcher-equipped golf carts; each first aid station was equipped with automated external defibrillators, biophone telemetry, portable suction and oxygen equipment; major medical equipment including monitor defibrillators, telemetry units, portable suction units, oxygen tanks, hand-held radios, stretchers and beds; trauma and immobilization supplies; assorted intravenous crystalloid fluids and administration sets; medical kits containing diagnostic tools and advanced airway management equipment; and basic wound care supplies alongside over-the-counter oral medications (analgesics, antacids, salt tablets).	Outcomes for a total of 298 patients included 35 hospital transports (11.75%; 28 by ambulance, 7 by private vehicle) and 2 cardiac arrests (0.67%); specific complaints consisted of headache (74; 24.8%), nausea (52; 17.5%), syncope (29; 9.7%), lacerations (25; 8.4%), dizziness (16; 5.4%), blisters (14; 4.7%), abdominal pain (11; 3.7%), abrasions (11; 3.7%) and shortness of breath (8; 2.7%); 4 cases each (1.3%) of chest pain, fatigue, back pain and knee injuries; 3 cases each (1.0%) of ankle injury, wrist injury, fall/multiple complaints, foreign body in the eye and heat exhaustion; 2 cases each (~0.67%) of supraventricular tachycardia, epistaxis, hand injury and cold exposure; and 1 case each (0.33%) of chronic obstructive pulmonary disease, foot fracture, finger dislocation, hip injury, broken cast, burn, sunburn, bee sting, hypoglycaemia, diabetes, sore throat, heartburn, eye haematoma, seizure, burned eye, asthma and broken fingernail.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Dutch, 2008	Spectators; Staff	Sport	Medical resources included the deployment of St John Ambulance for on-site treatment.	Outcomes included 98.04% of patients being managed on-site without hospital transfer and 1.96% (69 total) requiring ambulance transport; specific conditions requiring transport comprised 11 fractures/dislocations (15.9%); 7 cases each (10.1%) of collapse for investigation and cardiac chest pain; 6 lacerations (8.7%); 5 cases each (7.2%) of soft tissue injury, head injury and anaphylaxis/significant allergy; 4 cases each (5.8%) of dehydration/heat exhaustion and acute abdominal pain; 3 cases each (4.3%) of acute focal neurology/stroke, seizure and cardiac arrhythmia; 2 cases of altered conscious state (2.9%); and 1 case each (1.4%) of third-trimester hypertension, multiple injuries, vomiting/diarrhoea and burns.
Ghaznawi, 1987	Pilgrims	Religious	Heat- and health-related mitigation measures included the provision of free health services to all pilgrims by the Ministry of Health; deployment of specialized heatstroke treatment infrastructure, including 64 Makkah Al-Mukarramah body cooling units; allocation of 4635 hospital beds specifically for heatstroke and heat exhaustion patients across Hajj sites; introduction of a mandatory reporting system for cases of heat-related illness to improve surveillance and response; distribution of umbrellas and provision of (continues)	Outcomes for the 1985 Hajj season included 2134 heatstroke cases (251 per 100 000 pilgrims) and 15 560 heat exhaustion cases (1826 per 100 000); total deaths from all causes reached 1784, of which 1012 were explicitly due to heatstroke (615 occurring within health facilities and 397 outside).

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
			(continued) cooled drinking water throughout the day at all sites; distribution of preventive health packs; and comprehensive pre-travel and on-site multimedia health education campaigns focusing on heat-related-illness prevention and emergency medical guidance.	
Grange, 1999	Spectators	Music	Interventions involved on-site medical coverage with first aid stations and arranged transport to a hospital when needed.	Outcomes for a total of 1492 patients across all music types included 885 trauma complaints (driven primarily by 308 musculoskeletal, 293 dermal and 164 head injuries) and 607 medical complaints (driven by 127 alcohol/drug-related, 64 syncope, 62 dizziness, and 54 each for gastrointestinal and respiratory issues); broken down by genre, rock concerts (n=653) generated 375 trauma cases (57.4%; led by 115 head, 111 musculoskeletal and 103 dermal injuries) and 278 medical cases (42.6%; heavily led by 93 alcohol/drug-related); whereas non-rock concerts (n=839) generated 510 trauma cases (60.8%; led by 197 musculoskeletal and 190 dermal) and 329 medical cases (39.2%; led by 50 syncope and 45 gastrointestinal cases). Various minor complaints accounted for the remainder across all categories.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Khan, 2017	Pilgrims	Religious	Medical resources and protocols included 36 <i>maktab</i> tent clinics and central tent clinics in Mina and Arafat established to deliver on-site emergency care for heat illness; and an emergency response plan comprising rapid cooling followed by an assessment of related risk factors such as diabetes mellitus, hypertension, cardiovascular morbidity, respiratory disease, mental health disorders and contributory medication history.	Outcomes for all patients (100% presenting with heat-related illnesses) included etiologies of physical exertion while exposed (79; 89.8%), sun exposure (76; 86.4%) and shade exposure (12; 13.6%); exposure durations of 2–3 hours (41; 46.6%), 3–4 hours (37; 42.1%) and 1–2 hours (10; 11.4%); symptoms comprising weakness, fatigue and lethargy (45; 51.1%), nausea (34; 38.6%), dizziness (32; 36.4%), breathlessness (16; 18.2%), 15 cases each (17.1%) of thirst and cramps, headache (12; 13.6%), and 2 cases each (2.3%) of vomiting and oedema; and clinical signs comprising 59 cases each (67.1%) of hot to touch and hypertension, pale perspiring skin/heat exhaustion (47; 53.4%), 34 cases each (38.6%) of restlessness, agitation, irritability and tachypnoea, rapid weak pulse (32; 36.4%), hypoglycaemia (24 of 42 tested; 57.1%), strong bounding pulse (21; 23.9%), delirium (18; 20.5%), hypotension (15; 17.1%), confusion (12; 13.6%), flushed dry skin/heatstroke (11; 12.5%), 4 cases each (4.5%) of syncope, unconsciousness, coma and loss of bowel/bladder control, 2 cases each (2.3%) of haematuria and death, and 0 rashes.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Nouhi, 1992	Pilgrims	Religious	Protocols for immediate on-site management of heatstroke patients by the medical team in Mina included rapid cooling via immersion in a tub containing iced tap water; initial immersion in water at a temperature of 15 °C followed by the addition of ice after approximately 5 minutes; and simultaneous skin and limb massage to prevent peripheral vasoconstriction.	Outcomes for 304 heatstroke cases included ~82% minor and ~18% major severity, with presentation body temperatures of 38–40 °C (65%), 40 °C (28%), and <38 °C (7%); 4% presented with associated diseases (cardiovascular disease, diabetes, chronic obstructive pulmonary disease and hypertension), 2% developed hypothermia following treatment and mortality was 3.5%; clinical symptoms, presented in descending order of frequency, as tachycardia in major heatstroke (90%); 80% each for hot/dry skin, skin flushing, and headache/dizziness; tachycardia in minor heatstroke (60%); moist skin (30%); bleeding (25%); dyspnoea (10%); 9% each for vomiting and nausea; 8% each for cyanosis and stupor; delirium (5%); diarrhoea (4%); and 3% each for convulsions, coma and wheezing.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Perron, 2005	Spectators	Sport	Medical resources included two emergency care centres for patron evaluation and treatment.	Outcomes across two emergency care centres included 15–74 patients treated per football game (mean 36), with the vast majority presenting for presumed heat-related illnesses, including dehydration, heat cramps and syncope/near-syncope.
Tajima, 2020	Spectators	Sport	Medical resources and protocols included stadium spectator medical rooms with physician and nurse staffing scaled to crowd size; one dedicated ambulance per venue coordinated for rapid hospital transfer; environmental heat stress monitoring using wet bulb globe temperature; heat-specific public health announcements encouraging hydration, shade-seeking and early medical presentation; active multidisciplinary stadium patrols to identify and guide unwell spectators to care; medical kits equipped with cooling supplies, fluids, oxygen, monitoring devices and automated external defibrillators; and adherence to national infection control protocols.	Outcomes for spectator medical room presentations included wounds, scratches and abrasions (84; 18.7%); heat illness (52; 11.6%); 49 cases each (10.9%) of gastrointestinal disorders and bruises/sprains; headache (35; 7.8%); dizziness (33; 7.3%); fever (26; 5.8%); fatigue (15; 3.3%); consciousness disorders, including alcohol-related (12; 2.7%); fractures/dislocations (10; 2.2%); and 5 cases each (1.1%) of chest pain and respiratory discomfort.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Tanaka, 2023	Spectators	Sport	Medical resources and protocols included spectator clinics staffed by emergency physicians and nurses; designated medical facilities comprising 8 hospitals inside and 27 hospitals outside Tokyo; ambulances crewed by three emergency medical technicians including at least one paramedic; scheduling modifications that changed the start times of selected events to cooler early morning or evening hours; and heat stress notifications based on wet bulb globe temperature thresholds.	Outcomes for 541 non-athletes included 255 injuries (47.1%), 161 non-heat-related illnesses (29.8%) and 125 heat-related illnesses (23.1%; 80 female, 45 male); 100 cases (18.5%) required hospital transport (73 by other vehicles, 27 by ambulance), resulting in 9 hospitalizations, 3 of which required tertiary emergency care; specific medical complaints included headache (23), non-infectious stomach pain (15), upper respiratory tract infections (5) and infectious gastroenteritis (4); and severe presentations included cardiogenic cardiac arrest (successfully resuscitated on-site), shock from melaena, dyspnoea (pulmonary embolism/deep vein thrombosis), altered consciousness (diabetic ketoacidosis), stroke and chest pain.

First author, Year	Study population	Type of event	Heat/health-related mitigation measures	Health outcomes and number of cases
Wetterhall, 1998	Officials; Olympic family members; media; volunteers; spectators	Sport	Heat and health-related mitigation measures included extensive on-site medical infrastructure featuring one central polyclinic, sports medicine stations, 84 spectator care stations and mobile aid teams; high-density medical coverage with spectator stations and one mobile aid team per 20 000 spectators equipped for immediate care of dehydration, heat cramps and syncope; a heat illness surveillance system utilizing logbooks and standardized forms faxed every 2 hours to a central unit for real-time monitoring and rapid resource reallocation; coordination with emergency medical services and designated referral hospitals, with at least one pre-assigned ambulance per 20 000 spectators; and public health preparedness integrating concerns relating to subtropical climate heat stress into medical service planning and staffing levels.	Outcomes and demographics for 10 715 total visits (893 repeat (8.3%); mean age 33.9 years, age range 0–94; 53.4% male) included 5925 other illnesses (55.3%), 3734 injuries (34.8%) and 1056 heat-related illnesses (9.9%); broken down by group in descending order of volume, spectators made 3482 visits (101 repeat (2.9%); mean age 32.6, age range 0–94; 38.1% male) presenting 1685 other illnesses (48.4%), 1045 injuries (30.0%) and 752 heat-related illnesses (21.6%); volunteers made 3280 visits (304 repeat (9.3%); mean age 34.4 years, age range 10–85; 46.3% male) presenting 1821 other illnesses (55.5%), 1272 injuries (38.8%) and 187 heat-related illnesses (5.7%); officials made 890 visits (133 repeat (14.9%); mean age 44.4 years, age range 15–75; 83.1% male) presenting 659 other illnesses (74.0%), 225 injuries (25.3%) and 6 heat-related illnesses (0.7%); media representatives made 779 visits (63 repeat (8.1%); mean age 39.6 years, age range 16–77; 83.3% male) presenting 602 other illnesses (77.3%), 167 injuries (21.4%) and 10 heat-related illnesses (1.3%); and the Olympic family made 480 visits (78 repeat (16.2%); mean age 41.8 years, age range 0–84; 61.5% male) presenting 385 other illnesses (80.2%), 89 injuries (18.5%) and 6 heat-related illnesses (1.2%).

Annex 3.2 Heat-related versus non-heat-related medical encounters and patient dispositions

First author, year	Total cases/ encounters	Total heat-related	Heat stroke	Heat exhaustion/ syncope/ dehydration	Total non-heat-related	Trauma, injuries and skin burns	Exacerbated comorbidities and medical (cardiac, respiratory, gastrointestinal, etc.)	Managed on-site (first aid)	Transferred to hospital	Deaths
Seiler, 2025	147	Grouped	NR	Grouped	Grouped	Grouped minor trauma	Cardiac and stroke-like symptoms noted in transferred patients	89 (60.5%)	15	0
Samarkandi, 2025	1183 (<i>survey</i>)	474 <i>(severe heat symptoms)</i>	NR	NR	NR	NR	NR	NR	NR	NR
Rahim, 2025	822	0 reported	0	0	822	0	102 acute gastroenteritis (AGE); 715 respiratory (upper respiratory tract infection, URTI)	NR	NR	0
Mercalli, 2025	213	23	0	23	190	74 (included 7 burns)	30 cardiovascular; 16 gastroenterological	173	31	0
Habrat, 2025	123	21	21 (<i>hyper-thermic</i>)	0	102	NR	Intoxication and cardiac arrests noted	0	123	NR
Collins, 2024	NR	40–60% of all cases	NR	Grouped	40–60%	NR	NR	NR	NR	NR
Maleczek, 2022	13 759	NR	NR	NR	13 759	6241 trauma; 178 burns	443 gastrointestinal; 100 respiratory; 908 altered mental state	~13 147	612	0
Imbriaco, 2022	31	0 reported	0	0	31	4	27 non-traumatic	31	NR	0
Almuzaini, 2021	98	98	50	48	0	0	0	49	49	0
Nayar, 2020	161 (<i>post-event</i>)	NR	NR	NR	161	117 leg pain; 105 joint pain	Blood pressure and glucose fluctuations noted	89 (<i>Self-treated</i>)	6	NR

First author, year	Total cases/ encounters	Total heat-related	Heat stroke	Heat exhaustion/ syncope/ dehydration	Total non-heat-related	Trauma, injuries and skin burns	Exacerbated comorbidities and medical (cardiac, respiratory, gastrointestinal, etc.)	Managed on-site (first aid)	Transferred to hospital	Deaths
Yezli, 2019	1801 (<i>survey</i>)	NR	NR	NR	NR	NR	NR	NR	NR	NR
Ranse, 2019	197	NR	NR	NR	197	13 lacerations	94 headaches; 12 Intoxication	188	7	0
Khan, 2018	394 013	83* (<i>in tent clinics</i>)	48	35	~393k	96 151 musculoskeletal/ orthopaedic	18 314 cardiac; 18 621 respiratory; 209 856 infections	~392k	1453	163
DeMott, 2018	180	158 (<i>environmental</i>)	NR	Grouped	22	32	112 illness; 39 mental health	NR	168	0
Abdelmoety, 2018	267	267	80	187	0	0	exacerbated diabetes (23 cases) and hypertension (13 cases)	246	~7	~6
Ho, 2014	2140	~406 (19%)	NR	Grouped	~1734	~1262 (59%) musculoskeletal / trauma	Grouped	~2132	~8	NR
Chia, 2011	1337	NR	NR	NR	1337	NR	1 dissecting aneurysm noted	NR	~144	NR
Yazawa, 2007	237	9	NR	9	228	95 trauma	2 alcohol-related	174	63	0
Olapade-Olaopa, 2006	494	NR	NR	NR	494	475 trauma	Grouped	444	39	0
Lukins, 2004	1870	143	NR	143 (<i>rehydration unit</i>)	1727	NR	NR	1381	465 (<i>to field hospital</i>)	0
Griffith, 2004	251	NR	NR	NR	NR	NR	NR	~121	130	NR
Feldman, 2004	1205 (<i>records</i>)	148	NR	Grouped	1057	123 trauma	91 gastrointestinal; 79 respiratory; 30 intoxication	795	24	0

First author, year	Total cases/ encounters	Total heat-related	Heat stroke	Heat exhaustion/ syncope/ dehydration	Total non-heat-related	Trauma, injuries and skin burns	Exacerbated comorbidities and medical (cardiac, respiratory, gastrointestinal, etc.)	Managed on-site (first aid)	Transferred to hospital	Deaths
Grange, 2003	485	13	NR	Grouped	472	176 soft-tissue/ orthopaedic; 10 burns	19 gastrointestinal; 9 respiratory; 4 cardiac	NR	NR	NR
Seraj, 1991	34	34	34	0	0	0	0	NR	NR	NR
Gustafson, 1987	24 747	NR	NR	Grouped	NR	Grouped (falls/ cuts)	12 cardiac arrests (10 resuscitated); diabetic emergencies	23 836	911	2
Baker, 1986	1783	232	NR	213 (illness) + 19 (dehydration)	1551	622 trauma; 150 dermal	140 gastrointestinal; 35 cardiac; 15 asthma; 11 diabetes	~1692	91	NR
Pons, 1980	298	4	NR	3	294	50 lacerations/ abrasions; 1 sunburn	8 asthma/chronic obstructive pulmonary disease; 2 cardiac arrests	263	35	0
Dutch, 2008	3514	4	NR	4	3510	11 fractures; 6 lacerations; 1 burn	10 cardiac chest pain/ arrhythmia	3445	69	0
Ghaznawi, 1987	17 694	17 694	2134	15 560	0	0	NR	NR	NR	1012
Grange, 1999	1492	28	NR	26 (Illness) + 2 (Dehyd)	1464	885 Trauma; 293 Dermal	54 respiratory; 38 gastrointestinal; 4 cardiac arrests	1492	NR	0
Khan, 2017	88	88	Grouped	Grouped	0	0	57.1% hypoglycaemic upon testing	NR	NR	2
Nouhi, 1992	304	304	304	0	0	0	4% had pre-existing cardiovascular illness, chronic obstructive pulmonary disease, diabetes	304	NR	~11
Perron, 2005	~720	"Vast majority"	NR	Grouped	NR	NR	NR	NR	NR	NR

First author, year	Total cases/ encounters	Total heat-related	Heat stroke	Heat exhaustion/ syncope/ dehydration	Total non-heat-related	Trauma, injuries and skin burns	Exacerbated comorbidities and medical (cardiac, respiratory, gastrointestinal, etc.)	Managed on-site (first aid)	Transferred to hospital	Deaths
Tajima, 2020	449	52	NR	Grouped	397	133 wound, sprain or bruise	49 gastrointestinal; 26 fever; 12 consciousness disorder	~449	NR	NR
Tanaka, 2023	541	125	NR	Grouped	416	255 injuries	161 illnesses (1 cardiac arrest, stroke, diabetic ketoacidosis)	441	100	0
Wetterhall, 1998	10 715	1056	NR	Grouped	9659	3734 injuries	5925 other illnesses	NR	NR	0

NR, not reported

Annex 3.3 Summary of Data extraction table, SR2

First Author, Year	Type of event	Study population	Study population (N)	Technological strategies / early warning system / pre-event planning	Technology Outcome	Early Warning & Crowd-Safety Outcomes	Operational Response (1), Equity (2), Cost (3), Feasibility(4) Acceptability (5)
Albalawi et al, 2025	Religious	Pilgrims	Refers to technology development	MAHYA app is designed for Hajj operations to overcome language and medical history access barriers, using facial recognition for rapid identification and immediate retrieval of medical data in emergencies.	MAHYA app improves emergency response efficiency by enabling rapid identification and immediate access to medical histories, reducing response times and improving care accuracy; uses facial recognition (Inception ResNet V1, Siamese networks) to overcome language and data access barriers during Hajj.	NR	(1) Immediate access to medical history improved response time and care accuracy, (2) secure login ensures data confidentiality, (3) NR, (4) successfully implemented MAHYA app in Hajj EMS, (5) NR
Alshamrani et al, 2025	Religious	Pilgrims	3	This study successfully demonstrates the potential of employing advanced technologies, such as wearable devices, machine learning algorithms, and remote sensing systems, to measure and analyze stress during the Hajj and Umrah pilgrimages	Wearable and analytics system enabled continuous monitoring of physiological, spatial, and subjective data during Hajj, identifying stress-fatigue patterns linked to activity metrics (e.g., steps, energy expenditure, distance), with key thresholds (>5,000 m) and high-burden locations (Mina, Muzdalifah), supports real-time monitoring and spatial-temporal risk detection, though no clinical impact assessed.	Real-time app alerts for abnormal physiological patterns (e.g., heart rate), enabling early intervention	(1) Real-time physiological alerts enable early intervention, strong data privacy, (2) cultural sensitivity, and informed consent measures, (3) NR, (4) high feasibility with 92% data continuity, (5) NR

First Author, Year	Type of event	Study population	Study population (N)	Technological strategies / early warning system / pre-event planning	Technology Outcome	Early Warning & Crowd-Safety Outcomes	Operational Response (1), Equity (2), Cost (3), Feasibility(4) Acceptability (5)
Daniel et al, 2025	Sport	Spectator	146	THiS-based surveillance integrating real-time data entry, automated analysis, customizable thresholds, alerts, QR self-reporting, and tablet-based capture; includes early warning with predefined thresholds, automated MoH alerts, coordinated teams, and multi-source data integration, supported by pre-event planning, training, communication setup, hardware provision, and prevention materials dissemination.	Real-time surveillance captured 146 cases across 31 sites, identifying syndromic (e.g., AGE, respiratory) and non-communicable events (injuries, heat illness); triggered automated alerts with immediate response preventing spread, supported real-time analytics, reporting, and cross-country coordination, enabling timely public health actions.	Threshold-based alerts with real-time processing and multi-source data; detected injuries (n=33), heat illness (n=22), and infectious disease (AGE, respiratory).	(1) Real-time threshold-based alerts enabled rapid response and outbreak containment, (2) NR, (3)NR, (4) high feasibility across 6 countries and 31 sites with scalable system, (5) high user acceptability (MoH engagement, daily use, user-friendly)
Naji et al, 2024	Religious	Pilgrims	713	A novel multi-objective optimization model (MO-CL) for mass gatherings that jointly optimizes ambulance fleet size, location, and dynamic redeployment. Distinguishes ALS and BLS units, accounts for crew fatigue by limiting redeployments, and is solved using a hybrid search approach (incremental, comprehensive, and reactive tabu search).	Model achieved ~95% coverage with a fleet of 64 ambulances (29 ALS, 23 BLS, 12 BLS backup) and 19 daily redeployments; coverage ranged ~96–99%, with higher resource needs during peak hours, reflecting system performance rather than health outcomes.	No real-time monitoring or early warning, retrospective EMS-based planning tool for ambulance allocation, NR	(1) NR, (2) NR, (3) reduced ambulance fleet size (ALS/BLS) while maintaining coverage, (4) feasible with limited redeployments (95% coverage achieved), (5) NR

First Author, Year	Type of event	Study population	Study population (N)	Technological strategies / early warning system / pre-event planning	Technology Outcome	Early Warning & Crowd-Safety Outcomes	Operational Response (1), Equity (2), Cost (3), Feasibility(4) Acceptability (5)
Al-Shaery et al, 2024	Religious	Pilgrims	64	Deep learning model construction and performance evaluation using each set comprising a Samsung Galaxy S22+ smartphone with Android 13 operating system with custom build android app, an Empatica E4 wristband, and a Zephyr BioHarness 3.0 belt.	ML model showed good performance for fatigue and emotional state prediction (cross-validation ~85.6% and ~82.2%, with similar holdout accuracy), but lower performance for activity classification (~42%) likely due to class imbalance; overall demonstrates acceptable generalization with room for improvement.	Physiological signal-based prediction of fatigue, emotional state, and activity to support crowd management	(1) NR, (2) limited equity (male-only participants), (3) NR, (4) feasible deployment of multimodal wearable system in real Hajj/Umrah settings, (5) NR
Alghamdi, et al, 2024	Religious	Pilgrims	Refers to technology development	The paper presents a multilingual healthcare chatbot built on domain-specific fine-tuned large language models, enhanced with synthetic data, retrieval-augmented generation (RAG), and a secondary AI fact-checking agent to deliver reliable, evidence-validated medical guidance to Hajj pilgrims	Healthcare chatbot achieved high accuracy and reliability, outperforming benchmarks by using RAG and synthetic data; improved robustness, language understanding, and reduced misinformation through evidence-based response verification.	NR	(1) NR, (2) culturally sensitive and ethically designed chatbot ensuring privacy, trust, and transparency, (3) NR, (4) high accuracy and performance, (5) NR
Al-Shaery et al, 2022	Religious	Pilgrims	2	Machine learning classification models to predict pilgrims' current activity, fatigue (physical status), and emotional (psychological) state.	In addition, the physical status detection model performs very well (10-fold cross validation accuracy of 0.98) but the emotion detection classifier unperformed (10-fold cross validation accuracy of 0.64).	GPS and wearable-based framework for automated crowd monitoring and data collection	(1)NR, (2) NR, (3) NR, (4) NR, (5) NR

First Author, Year	Type of event	Study population	Study population (N)	Technological strategies / early warning system / pre-event planning	Technology Outcome	Early Warning & Crowd-Safety Outcomes	Operational Response (1), Equity (2), Cost (3), Feasibility(4) Acceptability (5)
Alkassas et al, 2020	Religious	Pilgrims	1200	Electronic survey capturing demographics, comorbidities, medication use, skin color, and skin condition; XGBoost decision tree model used to identify key clinical predictors and develop a diagnostic classification tool for heat-related illness.	This study highlights the magnitude of HRIs among pilgrims in the 2018 Hajj season and provides a diagnostic tree that can aid in screening and risk stratification of these patients.	NR	(1) NR, (2) inclusive survey covering men, women, and multiple ethnic groups, (3) NR, (4) NR, (5) NR
Arbon et al, 2001	Other	Spectator	146 cases across 31 sites	Standardized dataset across mass gatherings used with regression modelling to predict patient presentations and hospital transports based on crowd, environmental, and event characteristics, supporting evidence-based medical planning.	Model performance/ outputs reported (prediction models), not an implemented technology outcome. The main patient-prediction model "accounts for 64% of the variance" in total presentations; hospital models account for 34% and 31% of variance respectively.	Pre-event decision-support predicting patient load and transport needs based on forecast conditions, NR	(1) NR, (2) NR, (3) NR, (4) indirect feasibility for planning models without implementation validation, (5) NR
Bowdish et al, 1992	Sport	Spectator	98 to 180 patients per race (mean ≈140)	Simple regression model predicting race-day patient load based on weather and race factors, with strong association to dew point, but limited predictive validity when applied to new data.	Significant statistical relationship between dew point and patient load ($r = .91$, $P < .01$) during 1983–1989. Model failed external validation in 1990 (poor predictive performance). Authors conclude regression analysis is inadequate as a reliable prediction tool for mass gatherings	Pre-event meteorological (e.g., dew point) predictive planning for patient volume, no real-time alerting capability, NR	(1) NR, (2) NR, (3) NR, (4) regression modelling feasible with public data but limited predictive value, (5) NR

Annex 3.4 Summary of data extraction table, systematic review 3

Authors	Event Type	Population	N and vulnerable population	Intervention (communication/ identification/ digital)	Health/heat outcomes	Knowledge/ behaviours	Process (outcomes and indicators)	Equity and uptake	Costs, feasibility and acceptability
Rahim 2025	Exhibition	Visitors	250 410; NR vulnerable	Multichannel heat communication + digital platforms, signage	No cases of heat-related illness; acute gastroenteritis (102), upper respiratory tract infection (715), COVID-19 (5)	Improved awareness (hydration, shade, symptoms)	Prevention-focused messaging; no system evaluation	Multilingual reach; uptake NR	Feasible at large scale; NR cost/ acceptability
Collins 2024	Sporting	Spectators	NR	Heat index (NWS categories)	Heat cases 0.34–1.93 per 10 000	NR	Observational only; no alert system	Access gaps noted	Feasible observational model
Cadet 2023	Sporting	Visitors	54; ≥65 (14.5%)	SMS public safety alerts	No effect on behaviour	High preference for SMS (~84%)	No significant associations ($P>0.05$)	Moderate uptake (582 enrolled); possible bias	Feasible; high acceptability
Tanaka 2023	Sports	Spectators	541; NR	WBGT alerts via smartphones	125 cases of heat-related illness (23.1%); 541 total cases	NR	Alerts used preventively; severity distribution reported	Universal access	Operationally feasible
Almuzaini 2021	Religious	Pilgrims	98; ≥60 (5.3%)	Clinical guidelines (no digital/ identification system)	Heat exhaustion (49), heat stroke (49)	Knowledge gaps in care	Moderate compliance; variable adherence scores	Limited inclusion (pilgrims <18 years old excluded)	Feasibility affected by data gaps
Alkassas 2021	Religious	Pilgrims	231; chronic disease groups	ML diagnostic model (XGBoost)	Heat stroke (14), HE (40)	NR	High diagnostic accuracy (93.6%); predictors identified	NR	Technically feasible

Authors	Event Type	Population	N and vulnerable population	Intervention (communication/ identification/ digital)	Health/heat outcomes	Knowledge/ behaviours	Process (outcomes and indicators)	Equity and uptake	Costs, feasibility and acceptability
Taibah 2020	Religious	Pilgrims	245; NR	Culturally tailored multichannel communication	NR	78% concerned about heatstroke	NR	Gender/ language limitations	Feasible but inclusivity issues
Yezli 2019	Religious	Pilgrims	1801; >57 years (23.4%)	Health education campaigns	Not assessed (KAP study)	KAP varies by demographics; knowledge–practice gap	Demographic associations identified	Inequities relating to education/ nationality	Feasible; limited behaviour change

KAP, knowledge, attitude and practices; NR, not reported; NWS, national weather service; SMS, short message service; WBGT, wet bulb globe temperature

