Stadiums as climate-exposed socio-technical infrastructures:
A scoping review of fragmented risks and emerging challenges

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January 2026

Preprint – Not peer reviewed

This manuscript is a preprint submitted to Safety Science.
It has not yet undergone peer review and should not be cited as a final publication.

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Highlights

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- Evidence on stadium-related climate risks is abundant but remains dispersed across disconnected disciplinary domains.
- Climate change is seldom considered explicitly and rarely linked to evolving hazard profiles.
- No existing study analyses compound or systemic climate risks in stadium environments.
- Heat-related behavioural and crowd-management risks are entirely absent from the stadium literature.
- The review proposes a hazard–exposure–vulnerability framework to integrate isolated findings and support future risk assessments.

Stadiums as climate-exposed socio-technical infrastructures: a scoping review of fragmented risks and emerging challenges

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Abstract

Stadiums are among the most climate-sensitive infrastructures in global sport, yet the evidence available to characterise their climate-related risks remains fragmented. Although billions of spectators attend sporting events each year and climate change is recognised as a multiplier of existing hazards, research on stadium environments continues to treat risks separately. Heat is examined through comfort or ventilation studies, precipitation through drainage engineering, wind through fluid dynamics, and energy through HVAC performance—almost always under present-day conditions and without reference to changing extremes.

We conduct a scoping review of stadium-focused studies across ten thematic domains to evaluate how climate-sensitive risks are currently addressed. Explicit references to climate change are scarce and largely confined to sustainability or energy-efficiency discussions. Existing contributions capture isolated components of hazard, exposure or vulnerability—such as semi-outdoor thermal comfort, structural behaviour, or drainage performance—but they remain conceptually disconnected. Crucially, no study addresses systemic or compound climate risks, and heat-related behavioural risks are entirely absent despite robust evidence linking high temperatures to aggression, agitation and increased medical demand during mass gatherings.

This review demonstrates that current knowledge is insufficient to anticipate how climate change will reshape stadium safety, operations and infrastructure performance. As a way forward, we propose the hazard–exposure–vulnerability ($A\times E\times V$) framework as a conceptual pathway to organise disparate findings, reveal missing interactions, and guide future climate-informed risk analyses for stadium systems.

Keywords: stadiums, climate risk, infrastructure, heat stress, compound risk, vulnerability, scoping review

1. Introduction

Sport constitutes a global socio-economic system involving billions of participants, spectators and media viewers, and depending increasingly on large and technically complex infrastructures. Climate change is already reshaping this system. Rising temperatures, more frequent heatwaves, shifts in seasonal patterns and intensifying extreme weather affect athlete performance, event scheduling, spectator safety and facility operation. Recent reviews show that climate change is becoming a multisectoral constraint on participation, training and health (Bernard et al., 2021; Orr et al.), and the IPCC identifies outdoor physical activity as highly sensitive to warming and extreme heat (IPCC, 2022). Yet stadiums—among the most emblematic and operationally critical infrastructures in sport—remain under-examined from a climate-risk perspective.

Stadiums combine multiple pathways of climatic exposure: dense and thermally stressed crowds, energy-intensive cooling systems, complex geometries, sensitive natural or hybrid playing surfaces, and dependencies on urban drainage, mobility and emergency services. They also structure large economic flows linked to professional leagues, mass events and tourism. Despite this, research addressing climate-relevant risks is fragmented across domains and rarely connected to climate science.

Thermal comfort and heat stress are mainly investigated through microclimate engineering and CFD modelling (Bouyer et al., 2007; Guo and Sun, 2024; Ghani et al., 2021; Collins et al., 2024), typically under present-day weather. Energy and HVAC studies quantify cooling loads or operational optimisation (Sofotasiou et al., 2015; Bialy and Ghani, 2021; Khalil et al., 2016), but treat climate as a static boundary condition. Hydrology and drainage work examine runoff or pluvial flooding (Duarte et al., 2013; Scholz et al., 2006; Wang et al., 2022), with no connection to intensifying rainfall extremes. Studies on material degradation and corrosion highlight marine or polluted exposures (Krolikowska and Bonora, 2023; Tominaga and Shirzadi, 2023), but without long-term climatic trajectories. Turf and irrigation studies address water scarcity (Rossini et al., 2019; Harivandi, 2012), but seldom in relation to future drought or heat regimes. Research on crowd management or emergency care (Liu et al., 2024) overlooks thermal conditions despite robust evidence linking heat to aggression, agitation and instability (Anderson et al., 2000; Anderson, 2001; Hsiang et al., 2013).

Across these domains, the same pattern emerges: relevant processes are well documented, but documented in isolation. Heat is studied without climate scenarios; precipitation without extremes; wind without storm projections; energy without climatic baselines; materials without environmental trajectories; hydrology without evolving rainfall regimes; and behavioural risks without thermal stress. As a result, stadiums are seldom conceptualised as coupled human–infrastructure systems exposed to climate hazards. Elements of exposure—such as heat-stress for professional players (Lindner-Cendrowska et al., 2024) or semi-outdoor spectator discomfort (Guo and Sun, 2024)—are rarely articulated as risk mechanisms. Components of vulnerability—thermal design, energy dependence, marine corrosion (Zhu, 2020a; Tominaga and Shirzadi, 2023)—remain unconnected.

This fragmentation limits the field's capacity to address the central question raised by climate change: not whether stadiums will face heat, storms, flooding, drought or material degradation, but how these hazards will intensify, interact and cascade across technical, organisational and human subsystems. Without a unified structure linking hazards, exposure and vulnerability, anticipatory analysis of compound events and systemic failures remains largely absent.

This scoping review addresses this gap by systematically analysing ten domains of climate-sensitive risk relevant to stadiums, using targeted Web of Science queries. These domains include heat stress, air quality, precipitation and flooding, wind and storms, energy and cooling demand, turf and water management, material degradation, behavioural risks, emergency operations and economic impacts. For each domain, we synthesise current knowledge, examine whether and how climate change is considered, and identify structural limitations that prevent a systemic understanding of stadiums as climate-risk systems.

The objective of this review is not to quantify risks for specific venues, but to consolidate the empirical and conceptual basis needed to support climate-informed adaptation and risk management. In doing so, it establishes the foundation for an integrated hazard–exposure–vulnerability approach capable of bridging disciplinary silos and enabling more coherent climate-risk thinking for stadium infrastructures.

2. Methods

2.1. Conceptual framing and identification of risk domains

This study uses a structured scoping review approach to examine how climate-sensitive risks affecting stadiums are addressed in the scientific literature. The objective is not to produce an exhaustive synthesis, but to map the thematic coverage, dominant perspectives, and major gaps within a heterogeneous and highly fragmented field.

The conceptual framing draws on two complementary bodies of knowledge. First, existing reviews on climate change and sport (Bernard et al., 2021; Orr et al.) document the growing influence of climatic stressors on sport systems, while noting a persistent emphasis on athlete performance and health rather than on sport infrastructures. Second, established climate-risk frameworks—including hazard–exposure–vulnerability concepts widely used in IPCC assessments—provide a broader understanding of how climatic hazards affect built environments, critical infrastructures and mass gatherings.

Based on this dual perspective, ten climate-sensitive risk domains relevant to stadium ecosystems were identified *a priori*. These domains span human, environmental, structural, and technical–operational dimensions and are summarised in Figure 1. They do not constitute an exhaustive taxonomy, but a pragmatic structure for organising the subsequent literature analysis.

2.2. Overall scoping review design

A scoping review methodology was adopted to explore the breadth, focus and limitations of stadium-related research. This approach is well suited for mapping research landscapes characterised by disciplinary silos, heterogeneous data, and variable methodological traditions. The goal is to identify how each risk domain is treated, which assumptions dominate, and where structural gaps persist, rather than to conduct meta-analysis or quality appraisal.

2.3. Literature search strategy

A targeted search was performed in the Web of Science Core Collection. For each of the ten risk domains, a domain-specific topic query was constructed by combining the term “stadium” with keywords representing relevant hazards, mechanisms or operational issues (e.g., “heat stress”, “ventilation”, “drainage”, “wind load”, “corrosion”, “energy demand”).

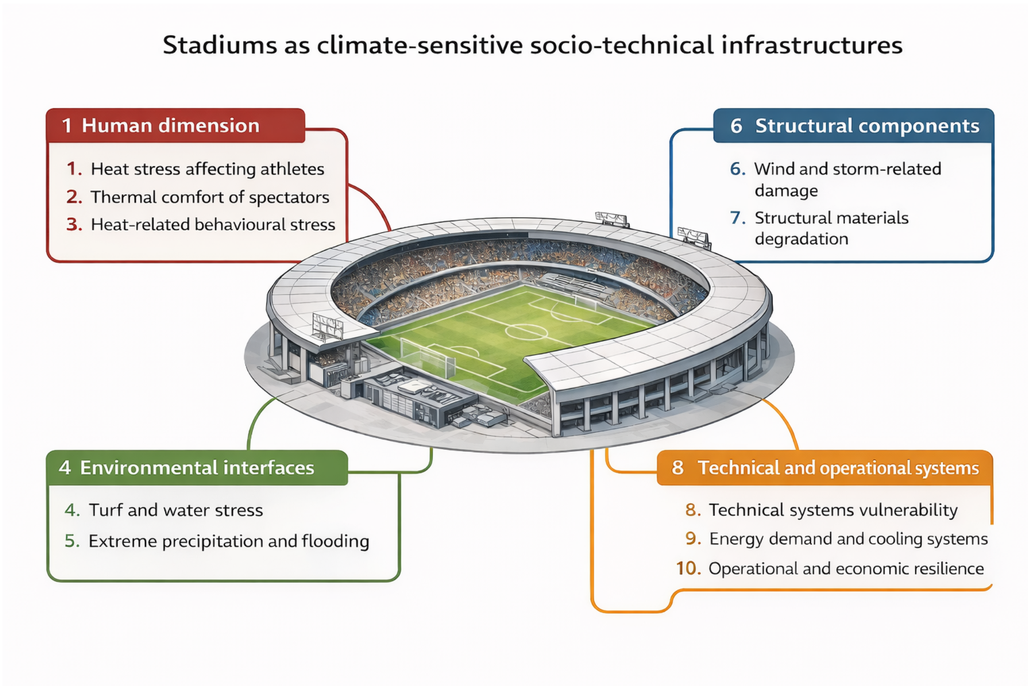

Figure 1: Climate-sensitive risk domains relevant to stadium environments, grouped into human, environmental, structural, and technical–operational dimensions.

This stadium-centred strategy was chosen to ensure that the review remained focused on the specific object of interest—stadiums—rather than on broader sport or event contexts that may involve distinct infrastructures and exposure pathways.

Table 1 presents the query design and number of retrieved records for each domain. The record counts are reported for transparency only and are not interpreted as indicators of scientific attention or evidence strength.

2.4. Screening and thematic classification

Titles and abstracts of retrieved records were screened to assess their relevance to stadium environments. Studies explicitly examining stadiums, semi-outdoor arenas, indoor halls or adjacent infrastructures were retained. Each publication was assigned to a primary risk domain based on its dominant focus and methodological orientation.

The analysis concentrated on identifying:

Table 1: Overview of stadium-focused Web of Science queries and number of records identified for each climate-sensitive risk domain.

#	Risk domain	Web of Science query	Records
1	Extreme heat	TS = stadium AND (heat OR “heat stress” OR WBGT OR “extreme heat”)	141
2	Thermal comfort	TS = stadium AND “thermal comfort”	40
3	Aggression / violence	TS = stadium AND (aggression OR violence) AND heat	0
4	Sports turf and water stress	TS = “sports turf” AND (drought OR heat OR irrigation OR fungus)	23
5	Extreme precipitation	TS = stadium AND (flood OR drainage)	50
6	Wind, storms and hail	TS = stadium AND (wind OR storm OR hail)	227
7	Structural degradation	TS = stadium AND (corrosion OR deterioration)	40
8	Technical systems	TS = stadium AND (HVAC OR condensation)	11
9	Energy demand and cooling	TS = stadium AND (“energy demand” OR cooling)	89
10	Economic and operational resilience	TS = stadium AND stadium AND ("operating cost” OR "economic impact*” OR "facility management” OR "risk management” OR "business model” OR "infrastructure resilience”)	99

- the types of hazards, exposures or vulnerabilities addressed in each domain,
- recurring methodological assumptions (e.g., present-day baselines, single-design-day analyses),
- and notable thematic or conceptual omissions.

No attempt was made to evaluate study quality or to standardise findings across domains, as the aim was to assess conceptual coverage rather than evidence synthesis.

2.5. Treatment of climate change within the review

Explicit references to climate change, future warming scenarios or adaptation strategies were not required for inclusion. Instead, the review examined risks that are intrinsically climate-sensitive under present-day conditions. The relevance of climate change is therefore discussed in interpretive terms: whether reviewed studies incorporate climatic trends, acknowledge future hazard intensification, or implicitly describe mechanisms (hazards, exposure, vulnerability) that climate change is expected to amplify.

These cross-domain implications are synthesised in the Discussion, where the findings are interpreted within the broader context of climate-risk research and existing IPCC frameworks.

3. Results: Thematic synthesis of stadium-related risks

3.1. Overall distribution of studies across risk domains

The Web of Science queries reveal a highly uneven distribution of stadium-focused studies across the ten climate-sensitive risk domains (Table 1). Some domains are comparatively well represented, while others receive little to no explicit attention.

Wind- and storm-related risks dominate the corpus, with more than two hundred records addressing issues such as wind loads, storm damage and structural safety. Extreme heat affecting athletes and energy demand associated with cooling systems are also recurrent topics, reflecting longstanding concerns about thermal stress and operational performance during sporting events.

By contrast, other risk domains remain sparsely documented. Studies focusing on technical systems such as HVAC performance or condensation are limited, and sports-turf management under heat or water stress appears only modestly covered. Most notably, no stadium-focused publication explicitly addresses heat-related aggression or violent behaviour, despite the central role of crowd dynamics in mass-gathering environments.

Figure 2 summarises this landscape by mapping the relative density of publications across human, environmental, structural and technical–operational dimensions. Beyond differences in publication volume, the heatmap highlights a strong fragmentation: most studies address isolated risks within specific disciplines rather than systemic or interacting vulnerabilities.

Explicit references to climate change, future projections or long-term adaptation strategies remain rare across all domains. Where present, they are largely confined to discussions of energy efficiency or sustainability, rather than to the assessment of evolving climate hazards affecting stadium operations.

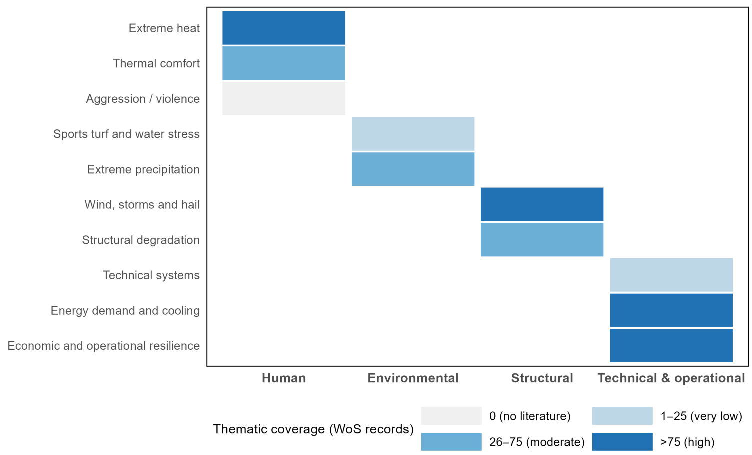

Figure 2: Fragmentation of the stadium-focused literature across climate-sensitive risk domains. The heatmap summarises the relative thematic density across human, environmental, structural and technical–operational dimensions based on abstract screening.

3.2. Heat stress and athlete performance

Across the 141 records retrieved under the "extreme heat" domain, the overwhelming majority of stadium-related studies focus on thermal comfort modelling, architectural design, energy systems, or mass-gathering medicine. Very few papers directly analyse athlete-level physiological strain or performance outcomes in hot stadium environments. This imbalance is striking given that elite competitions are increasingly held under thermal conditions exceeding recognised safety thresholds.

The clearest evidence comes from direct physiological monitoring during professional football competition. Aragón-Vargas et al. (2009) report pre-match hypohydration in several players (USG $\geq$ 1.020), mean body-mass losses of $\sim$3–4%, sweat losses exceeding 4 L, and core temperatures reaching or exceeding 39 °C during a match played at WBGT $\approx$ 32 °C. These values indicate that elite players already operate at or beyond the limits of compensable heat stress during routine competition, with a plausible negative impact on technical, cognitive and physical performance that remains largely undocumented.

Thermal risks are also evident in athletics. Kajiwara et al. (2005) show that summertime national track-and-field championships in Japan consistently occurred under WBGT values exceeding ACSM/JASA extreme-risk thresholds (WBGT > 28 °C), with globe temperatures up to 49 °C and track-surface temperatures approaching 60 °C. These conditions imply very high radiative and conductive loads for sprinters and jumpers, yet athlete-level physiological or performance assessments remain largely absent.

Threshold-based studies in arid environments provide additional context. Kumar and Sharma (2022) recalibrated WBGT, PET and UTCI for people exercising in semi-arid stadia, identifying a narrow comfort band (WBGT 23.8–28.1 °C) and recommending cessation of training at WBGT $\geq$ 40.8 °C. Although not conducted on elite athletes, these values frame the limited thermal margin available for safe high-intensity activity in many contemporary stadiums located in hot climates.

The only study in the corpus providing an explicit *prospective* assessment of athlete heat risk is Lindner-Cendrowska et al. (2024). Their biometeorological modelling for the 2026 FIFA World Cup indicates that 10 of 16 North American stadiums are expected to reach "very high" or "extreme" heat-stress categories during afternoon kick-off windows, with adjusted UTCI frequently exceeding 49.5 °C and predicted water-loss rates surpassing 1.5 $\mathrm{kg\,h^{-1}}$. These conditions approach uncompensable heat stress, with direct implications for both player safety and performance.

Evidence from mass-gathering medicine further illustrates the physiological burden of hot stadium environments, although typically centred on spectators rather than athletes. During the 1999 IAAF World Championships in Seville, Moreno Millán et al. (2004) documented 165 heat-related medical presentations out of 1338 consultations despite reinforced medical planning. Emergency-care analyses from football tournaments such as the UEFA Under-21 Championship similarly suggest that temperature, humidity, alcohol consumption and lack of free water meaningfully increase medical demand (Liu et al., 2024). While these studies focus on spectators, they underscore that stadium microclimates represent a genuinely hazardous thermal environment affecting all exposed populations.

Overall, the literature demonstrates that (i) elite competitions already take place under thermal environments exceeding recognised safety thresholds; (ii) athletes can experience substantial physiological strain (hyperthermia, dehydration) during matches in the heat; but (iii) robust quantification of associated performance decrements is almost entirely absent. Despite the clear relevance of increasing heat exposure for future competitions, explicit consideration of *climate change* is largely missing from athlete-centred studies. Most papers treat heat as a static environmental condition. Reviews of heat impacts on mass-gathering sports events identify climate change as a critical amplifier of future risk (Mason et al., 2024), yet athlete-level modelling integrating climate-scenario projections (e.g. CMIP6, SSPs) is practically non-existent. The gap between documented present-day heat strain and the lack of forward-looking climate-risk assessments represents a major blind spot in the stadium-sport literature.

3.3. Thermal comfort of spectators

The Web of Science query on *stadium AND "thermal comfort"* returns 40 records, but only a limited subset deals explicitly with the in-situ thermal experience of spectators and players inside stadiums or large sports venues (**?**Sofotasiou et al., 2015; Ghani et al., 2021; Losi et al., 2021; Guo and Sun, 2024; Collins et al., 2024; Li et al., 2022; Ashmawy et al., 2017; Qian and Yang, 2016). These studies fall into three broad categories: (i) empirical measurements and comfort surveys during matches or events; (ii) simulation-based design and control of semi-open or retractable-roof stadia; and (iii) methodological comparisons of thermal comfort indices for hot-humid or hot-arid environments. Many of the remaining records concern more generic sports buildings or gymnasiums and are only indirectly relevant to the stadium context.

Empirical work shows that spectator comfort in semi-open stadia is highly heterogeneous in space and strongly controlled by microclimatic variations. In a semi-open air-conditioned stadium in Qatar, 532 spectators reported mostly cool to neutral sensations; among seven candidate indices, WBGT showed the closest agreement with thermal sensation votes, with an average bias of only 8.8% and clearly outperforming PMV and other indices (Ghani et al., 2021). Field measurements and questionnaires in a semi-enclosed football stadium in Harbin indicate that overall comfort is most sensitive to the thermal environment, while spectators tolerate poorer acoustic conditions compared to other building types (Li et al., 2022). In a U.S. outdoor football stadium, more than 50 sensors documented strong within-stadium gradients in temperature, heat index and modified PET: mean conditions in seating areas were hotter than at a nearby weather station, and the most oppressive zones coincided with the majority of heat-related illnesses treated during hot games (Collins et al., 2024). These studies collectively show that relying on standard meteorological observations substantially underestimates the actual thermal burden experienced by spectators.

Simulation-based studies extend this empirical evidence by exploring design and control strategies. Early work by **?** couples wind-tunnel experiments with PET calculations to delineate aerothermal comfort zones in two semi-outdoor stadia, demonstrating the potential of virtual design tools to assess complex airflow and radiative environments. For the 2022 FIFA World Cup context, dynamic thermal modelling of semi-outdoor stadia in Qatar estimates that at least 115 MWh of cooling per game are needed to maintain tolerable conditions according to the Heat Stress Index, and discusses solar-based cooling as a partial mitigation option (Sofotasiou et al., 2015). A detailed CFD study of a 47 000-seat stadium in Doha shows that, even for outdoor conditions up to 48 °C and 70% relative humidity, a well-designed air-conditioning system combined with semi-open roofing can sustain neutral PMV for spectators while keeping WBGT on the pitch within FIFA safety limits; halving the cooling load still preserves acceptable comfort in most sectors (Losi et al., 2021). Complementary work on open-roof stadia focuses on optimising air distribution patterns to deliver comfort to both players and spectators under extreme hot-humid conditions (Ashmawy et al., 2017; Qian and Yang, 2016).

Only a few studies explicitly connect thermal comfort in stadia to climate change. Guo and Sun (2024) emphasise that semi-outdoor sports stadia are particularly susceptible to summer heat waves in the context of global warming and show, using UTCI-based field measurements in three Chinese climate zones, that the north stands systematically experience the highest thermal risk and that roof geometry strongly structures the spatial pattern of discomfort. Their analysis suggests that shading strategies are more effective than natural ventilation in reducing UTCI, pointing towards design levers for adaptation. However, even in this case the climatic forcing is treated as a present-day boundary condition: no study in this corpus systematically couples stadium-scale comfort assessment with future climate projections or scenario-based scheduling.

Overall, the thermal-comfort literature for stadia succeeds in characterising fine-scale microclimatic heterogeneity, in comparing and validating candidate comfort indices against subjective votes in hot climates, and in exploring design and HVAC strategies to maintain neutral or slightly cool sensations under extreme heat (**?**Sofotasiou et al., 2015; Ghani et al., 2021; Losi et al., 2021; Collins et al., 2024). What is largely missing is (i) a systematic treatment of spectators and players as vulnerable populations with differentiated sensitivities (age, health status, socio-economic factors); (ii) an explicit link-age between stadium-scale comfort and large-scale climate change scenarios; and (iii) an integrated view that connects local design choices (roof form, shading, ventilation, cooling) with exposure (where people sit, how long they stay) and vulnerability (pre-existing conditions, emergency response capacity). These gaps justify an A×E×V approach in which thermal comfort is not only a question of local microclimate control, but a dynamic risk emerging from the interaction between evolving hazards, the spatial distribution of spectators and athletes, and the structural and organisational characteristics of stadiums.

3.4. Human behaviour, excitation and violence

The targeted Web of Science search on behavioural responses in stadium contexts ("stadium AND (aggression OR violence) AND heat") returned **zero records**. This absence of evidence is itself a critical result. In contrast to other domains of stadium research (thermal comfort, heat stress, design or emergency medicine), no study in our corpus examines how heat exposure influences excitement, agitation, crowd behaviour, aggression or interpersonal violence inside sports venues.

The lack of stadium-focused work is particularly striking given that violent or agitated crowd dynamics constitute one of the central operational risks during large sporting events. Crowd incidents are well documented in the broader literature on sports safety and mass gatherings, yet none of these studies integrates thermal conditions, heat stress or microclimatic exposure as contributing behavioural drivers in stadiums. Behavioural risk is thus treated as largely independent from environmental stressors, despite well-established physiological and psychological pathways through which heat can amplify arousal, reduce self-regulation and increase the likelihood of impulsive or aggressive reactions.

This gap is amplified by findings from adjacent scientific domains (criminology, social psychology, behavioural economics, environmental epidemiology), which consistently report positive associations between high temperatures, agitation, aggression and various forms of interpersonal violence. None of this knowledge has yet been translated to stadium environments, even though these venues combine multiple heat-amplifying factors: high crowd density, prolonged exposure in confined seating, alcohol consumption, emotionally charged competitive contexts and, at times, limited ventilation. From a risk perspective, the complete absence of integrated *thermal–behavioural* assessment in stadiums constitutes a substantial blind spot.

Overall, the literature provides *no* empirical or modelling basis for understanding how heat modifies behavioural dynamics within spectators or between spectators and staff in stadiums. No study in our corpus considers whether extreme heat increases agitation or reduces compliance with safety protocols, nor how climate-driven intensification of heat waves may elevate behavioural and security risks in future competitions. This gap strongly justifies an A×E×V perspective, where behavioural vulnerability must be recognised as an integral component of stadium heat risk: hazards (A) are rising with climate warming, exposure (E) is structured by spectator density and seating patterns, and vulnerability (V) includes not only physiological susceptibility but also behavioural instability under thermal stress.

3.5. Sports turf under water stress, irrigation constraints and soil degradation

The sports-turf query returned 14 articles directly related to water use, drought tolerance, soil degradation or turfgrass physiological stress under sports-field conditions. Three broad themes emerged: (i) irrigation water scarcity and the viability of recycled or reclaimed water for sports fields (Harivandi, 2004, 2008; Rodríguez-Díaz and Weatherhead, 2011); (ii) turfgrass physiological responses to drought and heat, as well as breeding efforts to improve tolerance (Mutlu and Mutlu, 2014; Li, 2022; Cereti et al., 2004); and (iii) soil degradation processes (hydrophobicity, black layers, microbial imbalance) that influence water infiltration and thus drought risk (York and Lepp, 1994; Baldwin and Whitton, 1992; Gange et al., 1999; Bary and Gange, 2005). Only one article addresses climate-relevant greenhouse gas emissions from sports fields as an environmental externality of intensive irrigation and fertilisation (Riches and Porter, 2020).

Empirical studies consistently report that irrigation demand in sports turf is high and increasing under warm or dry climates. Two proceedings papers explicitly evaluate reclaimed municipal water as an alternative irrigation source for sports fields, emphasising salinity and sodium hazards as primary constraints to long-term use (Harivandi, 2004, 2008). A benchmarking study of golf courses in Spain shows that water-use efficiency varies widely and that standardised performance indicators can identify poorly performing systems, highlighting management variability as a key driver of water consumption (Rodríguez-Díaz and Weatherhead, 2011). In Mediterranean environments, partial restoration of evapotranspiration deficits—66% of ET—can maintain acceptable turf quality while reducing annual irrigation volumes by approximately 160 mm (Cereti et al., 2004).

Drought and heat are repeatedly shown to reduce turf quality through senescence, loss of membrane stability and impaired photosynthesis. A multi-year field experiment on creeping bentgrass demonstrates that sustained high temperatures (>30 °C) in subtropical zones sharply decrease turf quality and induce oxidative stress, osmotic imbalance and declines in chlorophyll and photochemical efficiency (Li, 2022). Genetic improvement is explored in bermudagrass populations, revealing substantial variation in drought tolerance, growth habit and recovery capacity, and identifying hybrid genotypes adapted to hot, dry environments (Mutlu and Mutlu, 2014).

Several articles demonstrate that soil microbial dynamics and degradation processes modulate turf response to drought. Fungal hydrophobicity in golf greens generates water-repellent soils that exacerbate localised dry spots (York and Lepp, 1994). Cyanobacteria-driven surface layers can further reduce drainage and promote anoxic black layers (Baldwin and Whitton, 1992). Conversely, arbuscular mycorrhizal fungi (AMF) can suppress undesirable *Poa annua* while benefiting *Agrostis stolonifera*, potentially reducing chemical inputs and increasing resilience under water stress (Gange et al., 1999). A complementary study shows that past fungicide applications do not significantly reduce AMF colonisation, suggesting that microbial-based solutions remain viable (Bary and Gange, 2005).

From an environmental-impact perspective, sports turf is shown to be a significant emitter of nitrous oxide due to frequent fertilisation and irrigation. Over 213 days, monitored sports fields emitted 2.5 times more N_2O than adjacent non-sports turf, with episodic methane emissions occurring after heavy rainfall events (Riches and Porter, 2020). This establishes a clear link between irrigation practices, soil moisture regimes and greenhouse gas fluxes, yet none of the studies integrate these findings with future climate-warming scenarios.

Overall, the literature provides detailed insights into turfgrass physiological responses to drought, the constraints of reclaimed-water irrigation and the role of soil biological processes in shaping water stress. Major gaps remain: (i) no study couples turfgrass water demand with climate-change projections of heat, aridity or ET_0; (ii) no integrated hazard–exposure–vulnerability framework links water stress with athlete safety, pitch performance or infrastructure degradation; and (iii) the interaction between drought, soil degradation and management inequalities is largely absent. These gaps strongly justify an A×E×V approach, framing drought hazard not only as a climatic constraint but as a risk emerging from soil condition, irrigation design, turf species selection and management intensity.

3.6. Flooding, drainage failures and emergency accessibility

The flood-related query yielded 12 relevant articles. Three domains dominate: (i) flood-induced loss of accessibility for stadiums and emergency services; (ii) engineering design of drainage, water-supply and flood-control systems; and (iii) structural or operational failures triggered by intense rainfall or poor hydraulic performance. Only a very small subset explicitly connects these issues to climate change, and no study links flood hazard to exposure–vulnerability dynamics for spectators or athletes.

Several studies examine how flooding disrupts emergency access. In Shanghai, scenario-based simulations show that increasing water depth rapidly isolates multiple stadiums, blocks ambulance routes and significantly increases response times for medical facilities, particularly in low-lying districts subject to sea-level rise and land subsidence (Wang et al., 2022). Coastal stadiums in China face similar risks: storm surges, extreme rainfall and inadequate drainage create recurrent safety concerns, yet these aspects have been largely overlooked during rapid construction cycles (Zhu, 2020b).

A second group focuses on hydraulic engineering and drainage. Generic drainage-design guidance exists but remains largely descriptive. Large-scale flood-control interventions in Rio de Janeiro's Maracanã district include detention reservoirs, enlarged culverts and a 2.4 km diversion tunnel designed to mitigate recurrent flash floods (Duarte et al., 2013). For multifunctional gymnasiums, predictive-control algorithms improve water-supply and drainage velocity management, addressing chronic instability in hydraulic systems (Dong and Wang, 2022). Structural case studies highlight the sensitivity of large-span stadium roofs to ponding: at La Cartuja Stadium in Seville, extreme rainfall revealed a significant reduction in membrane prestress requiring full roof substitution (Goberna Perez et al., 2021). Modular turf systems developed for Athens 2004 demonstrate the importance of engineered drainage layers for rapid field turnover (Nektarios and Ntoulas, 2008). Similar concerns appear in assessments of Istanbul football fields, where poor infiltration and uneven irrigation compromise drainage performance (Celik et al., 2019). Sustainable drainage options (SUDS) tested around the Celtic FC stadium show promise but are constrained by soil contamination and limited space (Scholz et al., 2006).

Only one article directly models human behaviour under flood-induced stress. An agent-based flood–pedestrian simulator combining hydrodynamics and crowd movement reveals that risk perception, congestion and behavioural feedbacks strongly shape evacuation trajectories in stadium settings, as demonstrated in the Hillsborough case study (Shirvani and Kesserwani, 2021). This illustrates that hydraulic design alone cannot safeguard evacuation performance.

Although several papers recognise that climate change intensifies coastal and pluvial flooding (Wang et al., 2022; Zhu, 2020b), none incorporates climate projections, extreme rainfall scenarios or changing storm-surge regimes into stadium-scale drainage modelling. No study connects flood hazard with spectator exposure, sheltering times or emergency medical vulnerability.

Overall, the literature documents local engineering solutions, case-specific drainage failures and accessibility disruptions, but lacks an integrated risk perspective. Key gaps include: (i) the absence of climate-scenario integration; (ii) no coupling of hydraulic performance with crowd dynamics; and (iii) no explicit A×E×V framing linking hazard intensity, spatial exposure of populations and vulnerability of stadium systems. These omissions justify a multi-layered A×E×V approach to future flood risk in stadium environments.

3.7. Wind, storms and hail impacts

The wind- and storm-related query identified ten relevant studies addressing wind loads, storm-induced pressures and extreme-wind hazards for large-span structures, including roofs directly comparable to stadium configurations. Three themes dominate: (i) aerodynamic characterisation of wind-induced pressures on long-span or curved roofs; (ii) sensitivity of stadium-like structures to fluctuating wind fields, typhoons and hurricanes; and (iii) hazard-modelling approaches that quantify return periods of extreme winds. No article in this corpus explicitly examines hail impacts, and only a subset mentions climate change through references to tropical-cyclone intensification or hurricane hazard.

Wind-loading mechanisms on large roofs are addressed through experiments, full-scale measurements and computational simulations. Studies show that long-span curved roofs experience strong suction zones and highly non-uniform pressure distributions that are extremely sensitive to approach-flow turbulence and boundary-layer representation (St. Pierre et al., 2005; Peng et al., 2014; Tamura and Ito, 1997). Full-scale wind measurements validate wind-tunnel data and confirm that stadium-like roofs with large cantilevers exhibit amplified dynamic response under gusty conditions (Tamura, 2008). CFD-based guidelines developed for complex urban geometries emphasise the importance of capturing separation and recirculation zones along sharp stadium edges (Tominaga and Mochida, 2008; Tominaga and Sato, 2011).

The hazard-oriented articles provide quantitative insights into the magnitude and frequency of damaging winds. Kasperski (2003) highlights the statistical instability of peak-wind estimation under non-stationary turbulence, underscoring design uncertainty for long-span roofs. Hurricane hazard analyses establish return periods for extreme gusts and provide wind-intensity curves widely used for structural safety assessments (Vickery and Masters, 2009). Pita and Pinelli (2015) frames wind hazard within a broader natural-hazards context and stresses the need to integrate structural vulnerability. Typhoon studies offer detailed wind-field characterisation relevant for stadiums in tropical regions, showing how fluctuating loads shape structural response (Mo and Li, 2015). Some of these works mention the increasing societal exposure to severe storms and the relevance of cyclone-intensity trends, providing indirect connections to climate-change risk.

None of the identified studies explicitly analyses stadiums under future climate scenarios, nor do they link wind hazard to spectator exposure, roof ageing, material vulnerability or operational continuity. No article assesses how projected increases in cyclone intensity, storm frequency or shifting storm tracks could affect structural loads on stadium roofs. Likewise, hail risk—despite its operational importance for roofing membranes and PV-equipped stadiums—is completely absent.

Overall, the literature offers robust aerodynamic and hazard-modelling foundations for understanding wind and storm impacts on large-span structures, but lacks a risk-oriented approach relevant for stadium environments. The absence of climate-change scenario integration, the lack of exposure–vulnerability considerations and the omission of hail impacts justify an A×E×V framework that connects intensifying storm hazards with the structural characteristics and population distributions specific to stadium settings.

3.8. Structural materials and long-term degradation

The query on structural materials and degradation returned a small subset of stadium-relevant studies (n = 7). Three themes dominate: (i) durability loss in ageing reinforced-concrete stands and shells; (ii) long-term deterioration of cable and steel roof systems; and (iii) corrosion hazards arising from environmental exposure and inappropriate material selection. Several complementary engineering studies on coatings or diagnostics are present in the corpus, but only those directly applicable to stadium structures are retained here. No article couples degradation with climate-change scenarios, nor quantifies future environmental aggressiveness.

Reinforced-concrete degradation in stadiums is examined through detailed diagnostic campaigns and structural assessment. Using a 90-year-old concrete stadium as a case study, Choi et al. (2016) document scaling, corrosion, carbonation and cracking through combined non-destructive and destructive methods. A probabilistic framework for assessing the technical condition of stadium stands is proposed by Dormidontova (2015), where statistical degradation parameters drive safety factors and fault indicators. At the scale of a major heritage structure, Zagaroli et al. (2025) quantify how reinforcement corrosion modifies seismic capacity and dynamic response of the Stadio Flaminio, integrating deterioration within a performance-based approach.

Long-term degradation of steel and cable systems is also documented. For a large-span cable-roof arena, Kmet and Tomko (2010) show that decades of environmental exposure alter geometry, stiffness and reliability, requiring nonlinear analyses calibrated by diagnostics and material testing. Material-level work by Tailor et al. (2019) demonstrates improved corrosion resistance of Zn–Al thermal-spray coatings under saline, humid and microbially aggressive environments representative of stadium steelwork. Two recent stadium-focused corrosion studies are particularly relevant: Krolikowska and Bonora (2023) report that corrosion failures at Al Bayt Stadium originated from basic material-selection and detailing errors, while CFD modelling by Tominaga and Shirzadi (2023) links airflow patterns around a coastal stadium to heterogeneous sea-salt deposition and spatially variable corrosion risk.

Across this literature, structural degradation is consistently treated as a material and component problem, with environmental exposure assumed stationary. No study examines how climate change might alter humidity regimes, salt fluxes, temperature cycles or pollutant loads. Nor is degradation linked to exposure (E) or to hazard interactions (A), despite clear implications for operational safety during mass gatherings. These gaps justify an $A \times E \times V$ perspective in which long-term degradation is considered a core dimension of vulnerability interacting with evolving climatic hazards and high dynamic occupancy in stadium environments.

3.9. HVAC systems, energy use and indoor environment

The query on HVAC, energy systems and indoor environment returned eight stadium-relevant articles. Three main themes emerge: (i) design and operation of HVAC systems specifically for stadiums and large indoor arenas; (ii) data-driven or model-based optimisation of thermal environment and energy use; and (iii) broader sustainability and decarbonisation frameworks in which stadiums are treated as high-impact commercial buildings. Many additional records concern generic HVAC control or indoor air-quality methods, but only those explicitly involving stadiums or large indoor sports spaces are retained here. Despite their diversity, these studies rarely address climate change directly and almost never couple HVAC performance to future climatic conditions.

Early work focuses on HVAC design for domed or enclosed stadiums. Towell (1998) discusses heating, ventilation and air-conditioning requirements in domed arenas, highlighting the complexity of providing adequate comfort under varying occupancy and climatic conditions. More recent contributions shift the emphasis to energy analytics and predictive control. Using six months of operational data from the Commerzbank Arena in Frankfurt, Schmidt et al. (2015) show that heating demand is primarily driven by outdoor air temperature, ventilation exhibits a strong daily pattern largely independent of temperature, and cooling responds to a combination of event schedule and air temperature. These results provide a basis for context-aware control and load-shedding strategies. In parallel, Seem (1998) and Seem (1997) develop and implement a pattern recognition adaptive controller (PRAC) that automatically tunes PI gains in HVAC systems; field tests demonstrate successful deployment in a wide range of buildings including large sports stadiums.

Several studies propose modelling approaches to predict the thermal environment in stadiums and optimise HVAC operation. For a 47 000-seat football stadium in Doha, **?** use steady-state CFD with conjugate heat transfer to simulate airflow, temperature and humidity distribution under different climatic conditions and duty cycles of the air-conditioning system. They show that, even for outdoor conditions up to 48 °C and 70% relative humidity, appropriately controlled cooling can maintain neutral thermal sensation in most seating zones while keeping WBGT on the pitch within FIFA safety limits; a 50% reduction in cooling load still preserves acceptable comfort for spectators and players. In a more generic large-space setting, Yoon et al. (2018) build artificial neural-network (ANN) models trained on CFDgenerated data to predict zone-level thermal variables (indoor air and mean radiant temperatures, clothing) in stadium stands using outdoor temperature and envelope surface temperatures as inputs. The approach is proposed as a way to control HVAC by zone in large spaces where sensor deployment is constrained by high occupant density.

The sustainability and climate dimension appears explicitly in a recent framework study. Kimanya et al. (2025) analyse the Mercedes-Benz Stadium as a case study for optimising distributed energy resources and HVAC–EV charging interactions using multivariate regression and a techno-economic tool, in a context where buildings contribute an estimated 17.5% of global greenhouse-gas emissions. Their scenarios span typical soccer matches to back-to-back concert events and illustrate how parametric analysis can balance affordability, resilience and decarbonisation goals. Complementary work on solar light pipes for daylighting in Chinese buildings identifies stadiums among the priority applications, noting that daylight-based lighting can reduce electricity demand if issues such as dust and condensation are resolved (Wu, 2008). However, even when climate mitigation is central, future weather or climate projections are not explicitly used as boundary conditions for HVAC design or control.

Overall, the literature provides detailed insights into HVAC design and operation for stadiums, including comfort-focused CFD analyses, data-driven energy characterisation and adaptive control strategies. It begins to link stadium energy systems with broader sustainability and greenhouse-gas reduction objectives. Yet key gaps remain: (i) no study couples HVAC performance with projected climate warming, humidity or heat-wave characteristics; (ii) exposure of spectators and athletes is reduced to comfort indices, without integration into risk metrics; and (iii) indoor-environment control is not embedded within an $A \times E \times V$ framework that recognises HVAC systems as both a protective barrier (reducing heat hazard indoors) and a vulnerability factor (through energy dependence and potential failure). Addressing these gaps requires explicitly linking HVAC design and operation to evolving climate hazards, dynamic exposure during events and the vulnerability of stadium infrastructures to both outdoor conditions and energy-system disruptions.

3.10. Energy demand and cooling

The WoS query on stadium "energy demand" and cooling yielded eight articles that explicitly quantify cooling loads, electricity use or HVAC-related energy performance in stadiums and large sports facilities (?Méndez and Bicer, 2020; Bialy and Ghani, 2021; Khalil et al., 2016; Schmidt et al., 2015; Katsaprakakis et al., 2019; Ghani et al., 2021; Liao and coauthors, 2025). Most studies focus on hot or warm climates (Qatar, Mediterranean Europe, Gulf countries, East Asia) and examine mechanical cooling strategies, load drivers and renewable-energy integration. Almost none explicitly connect energy demand to future climate warming or long-term thermal trends.

Several contributions provide detailed cooling-load assessments. Using dynamic thermal modelling, ? estimate that at least 115 MWh of cooling per match would be required to maintain acceptable conditions in semi-outdoor Qatar 2022 stadiums. CFD-based work by Bialy and Ghani (2021) shows that geometric optimisation—reducing the oculus area and smoothing the canopy—can halve the cooling load associated with hot-air infiltration. In a complementary analysis of outdoor air-conditioning, Khalil et al. (2016) demonstrate how inlet configuration and jet distribution strongly influence both comfort and the substantial energy penalty of cooling open spaces.

Operational studies highlight the dependence of cooling demand on usage patterns. Schmidt et al. (2015) show that heating, ventilation and cooling loads in the Commerzbank Arena are driven by different combinations of outdoor temperature, scheduling and event operation, implying contrasted predictability and opportunities for load management. At occupant scale, Ghani et al. (2021) report that WBGT-type indices best reflect thermal sensation in an open air-conditioned stadium under hot conditions, which is essential for defining realistic cooling set-points. On-site measurements in an indoor stadium by Liao and coauthors (2025) show that roof and infiltration loads dominate cooling demand and that ice-storage systems can shift electrical peaks.

A second group of studies addresses energy reduction or substitution. Méndez and Bicer (2020) estimate that wind farms located near three Qatar 2022 stadiums could fully cover match-day electricity use while avoiding tens of thousands of tonnes of CO_2 annually. In Crete, Katsaprakakis et al. (2019) evaluate a comprehensive retrofit of the Pancretan Stadium, combining PV, geothermal systems, biomass/solar combi units and lighting upgrades, and report substantial potential primary-energy savings and renewable penetration.

Overall, existing work provides a technically detailed picture of present-day cooling demand in stadiums and shows how geometry, HVAC configuration, operational patterns and on-site renewables influence energy use.

However, climate is treated as a fixed boundary condition: no study integrates warming scenarios, increasing humidity or changes in heat extremes when estimating future cooling loads. Likewise, energy demand is rarely examined in relation to occupancy patterns, safety thresholds or operational continuity. These gaps indicate that research on stadium cooling remains largely static despite rapidly evolving climatic and energy contexts.

3.11. Economic impacts of stadiums and sport events

The WoS query on economic impacts of stadiums and sport events yielded eight core articles that explicitly quantify or critically examine local economic effects of professional franchises, college sports or sport events (Agha and Taks, 2015; Lee et al., 2008; Salgado-Barandela et al., 2017; Barajas et al., 2016; Baade et al., 2011; Heller et al., 2018; Taks et al., 2011; Jasina and Rotthoff, 2008). Together, they cover three main themes: (i) theoretical frameworks contrasting large versus small events; (ii) empirical estimates of event or franchise impacts on sales, employment and tourism; and (iii) methodological critiques contrasting economic impact analysis and cost–benefit analysis or highlighting uncertainty. None of these studies considers climate change explicitly, and environmental or climate-related externalities only appear marginally, if at all, in keywords or broader discussions.

From a theoretical standpoint, Agha and Taks (2015) propose a resource-based framework that treats city size and event size as continua and introduce the concepts of event resource demand and city resource supply. Their model shows that small events often have a higher potential for positive net economic impact than large ones, and that hosting multiple smaller events can be a more favourable strategy than organising a single large event. This directly underpins the idea of an "event portfolio" spread over time rather than relying on one-off mega-events. At a broader disciplinary level, Salgado-Barandela et al. (2017) conduct a bibliometric review of economic impact studies in sport between 1984 and 2013, showing an evolution from a focus on mega-events to a wider range of facilities, franchises and small- to medium-sized events, and stressing the practical relevance of these analyses for the management of events and sport infrastructures.

Empirical studies provide heterogeneous but generally modest estimates of local economic gains. Using county-level employment and wage data, Jasina and Rotthoff (2008) find mixed effects of professional franchises, with some evidence of negative impacts on payrolls in specific sectors. For US college sport, Baade et al. (2011) show that men's basketball games have no statistically significant effect on taxable sales, while American football games generate only a modest increase of about 2 million US dollars per home game, casting doubt on the strong development claims often made by stadium boosters. In a different context, Heller et al. (2018) analyse national political conventions using hotel occupancy, price and revenue data, and estimate roughly 29 000 room nights and about 20 million US dollars in additional hotel revenue per convention, far below the 150-million-dollar impacts sometimes claimed for similar mega-events. At a smaller scale, Barajas et al. (2016) examine a two-day rally event in a small Spanish town and show that, while the race has favourable local economic effects, relatively simple changes in the event organisation could further increase its impact.

Two contributions focus on methodology and the treatment of benefits and costs. Taks et al. (2011) compare a standard input–output-based economic impact analysis (EIA) with a cost–benefit analysis (CBA) for a medium-sized junior athletics event. The EIA suggests a net increase in local economic activity of 5.6 million US dollars, whereas the CBA, which explicitly accounts for opportunity costs of stadium construction, ticket sales to residents and public good values, yields a negative net benefit of about 2.4 million US dollars. This illustrates how EIA tends to overstate net welfare gains. Lee et al. (2008) propose an analytical framework to evaluate the full economic impacts of a hypothetical bio-terrorist attack on a major league stadium, emphasising that indirect and behavioural linkages beyond direct losses must be captured; their case study estimates total losses between 62 and 73 billion US dollars, with the largest component coming from loss of life and a second major component from reduced demand for stadium visits.

Overall, this body of work demonstrates that (i) ex post economic impacts of stadiums and sport events are generally small or moderate compared with public claims; (ii) portfolios of small or medium events can be at least as attractive as large events when local resource constraints are taken into account; and (iii) methodological choices (EIA versus CBA, treatment of uncertainty, inclusion of non-market values) strongly condition conclusions about net benefits. However, the literature remains largely disconnected from climate and environmental change: climate-related risks, long-term sustainability of event calendars, or the interaction between physical vulnerability of stadiums and local economic impacts are not addressed. These gaps indicate that current economic analyses remain static despite rapidly evolving climatic and operational contexts.

4. Discussion

4.1. Fragmentation and disciplinary silos

Across all thematic domains, stadium-related risks are examined in isolation, with minimal interaction between physiological, engineering, environmental or organisational perspectives. Heat stress is analysed without reference to scheduling or crowd management; hydrological failures are assessed without considering occupant vulnerability; structural degradation is studied independently from future climatic aggressiveness; and energy-demand analyses ignore exposure or hazard dynamics. This fragmentation prevents current approaches from capturing how multiple stressors may interact or compound within complex stadium environments.

4.2. Climate change as a risk multiplier for stadiums

Only a small subset of stadium-focused studies explicitly considers future climate conditions, yet these contributions converge on a consistent message: climate change is likely to intensify familiar risks rather than introduce new categories of hazards.

Player-centred evidence is clearest in Lindner-Cendrowska et al. (2024), who project uncompensable heat stress at ten of sixteen venues for the 2026 FIFA World Cup, with adjusted UTCI values exceeding 49.5 °C and water-loss rates above 1.5 $kg\,h^{-1}$ during afternoon matches. Their prospective assessment demonstrates that thermal-stress mitigation and scheduling adjustments will become necessary even in the near term.

Spectator-oriented analyses reinforce this trend. Guo and Sun (2024) show that semi-outdoor stadiums in China already experience significant thermal discomfort during summer heat waves "due to global warming", highlighting structural susceptibility to rising ambient heat.

Energy- and cooling-focused work further illustrates the operational implications of warming climates. For the Qatar 2022 World Cup, **?** estimate that maintaining heat-stress thresholds in semi-open arenas requires at least 115 MWh of cooling per match. More recent optimisation studies, such as Zhang et al. (2023), integrate a wider envelope of meteorological conditions, signalling a shift toward climate-aware design and operation.

Hydro-climatic hazards follow the same pattern. Zhu (2020a) identify elevated flood-control risks for stadiums in marine climates, while turf-management studies emphasise irrigation pressure and soil-salinity risks during drought (Rossini et al., 2019; Harivandi, 2012). Although seldom framed explicitly in climate-change terms, these contributions point toward tightening resource constraints under warming scenarios.

Health-oriented work confirms that short-term weather variability already modulates stadium operations. During the UEFA Under-21 Championship, Liu et al. (2024) find that higher temperature and heat index were associated with increased medical demand among more than 70,000 spectators.

Taken together, the evidence indicates that climate change will amplify existing stressors: hotter environments for athletes and spectators, higher and more variable cooling demand, greater pressure on water resources, and more frequent hydrological disruptions. However, most studies still treat climate as a static boundary condition. Very few integrate climate scenarios or consider long-term trajectories across the operational lifetime of stadiums. This reinforces the need to move beyond present-day design assumptions toward forward-looking risk frameworks.

4.3. From match-day events to climate-stressed service archipelagos

The economic literature introduces an overlooked dimension of climate risk: the dependence of stadiums on event portfolios and service continuity over time. Several empirical studies show that ex post economic effects of franchises, college sports or short tournaments are modest and highly sensitive to methodological assumptions (Baade et al., 2011; Jasina and Rotthoff, 2008; Barajas et al., 2016; Heller et al., 2018; Taks et al., 2011). Cost–benefit analyses often yield negative net benefits once opportunity costs are accounted for (Taks et al., 2011).

Agha and Taks (2015) propose a resource-based model in which small and medium events often generate more favourable economic outcomes than mega-events, supporting a shift from reliance on singular flagship events to diversified portfolios. This interpretation aligns with the idea of stadiums functioning not as static venues but as nodes within an "archipelago" of recurrent events, services and uses.

The COVID-19 case study of the Adelaide Oval strengthens this view. Chan et al. (2021) show how stadium operations were gradually reconfigured across multiple phases of restricted capacity, public-health requirements and evolving risk. The stadium oscillated between operational states rather than simply "open" or "closed", with coordinated decision-making across public-health, stadium and league stakeholders.

From a climate-risk perspective, these findings are crucial. As climate hazards intensify—heatwaves, pluvial flooding, marine surges—attendance, revenue, scheduling feasibility and maintenance costs will fluctuate across seasons and event types. A diversified, flexible event portfolio may therefore confer higher resilience than dependence on a small number of climate-sensitive mega-events. Yet economic analyses remain disconnected from climate, exposure or vulnerability considerations. Bridging this gap requires conceptualising stadiums as dynamic service archipelagos embedded in evolving climatic, economic and organisational environments.

4.4. Heat-related behavioural risks as an overlooked dimension

Our scoping review found no stadium-focused studies addressing whether heat exposure modulates agitation, excitement, aggression or crowd instability. This is a major omission. Robust evidence from psychology, criminology and environmental social science consistently demonstrates that higher temperatures increase irritability, impulsive aggression and interpersonal violence (Anderson et al., 2000; Anderson, 2001; Hsiang et al., 2013; **?**).

One study in the stadium corpus provides indirect evidence. During the UEFA Under-21 Championship, Liu et al. (2024) observed that higher temperature and heat index were associated with increased medical requests among spectators. While not a behavioural study, this demonstrates that heat already affects crowd well-being and emergency-response load in stadiums.

Given that stadiums combine multiple heat-amplifying factors—density, alcohol, prolonged immobility, emotional arousal, constrained airflow—the absence of thermal–behavioural work represents a critical blind spot. As heatwaves intensify, both behavioural instability and medical vulnerability are likely to worsen, yet no study evaluates this risk pathway. This omission underscores the need for integrative climate–behavioural risk frameworks tailored to mass-gathering environments.

4.5. Toward an integrated hazard–exposure–vulnerability framework for stadiums

The hazard–exposure–vulnerability (A×E×V) framework provides a well-established foundation for analysing climate-related risks, emphasising that impacts arise from the interaction between hazardous climatic events, exposed elements and systems, and their underlying susceptibility or adaptive capacity (IPCC, 2022; Turner et al., 2003; Birkmann et al., 2013). While widely adopted in climate-risk research, this integrative perspective remains largely absent from stadium-focused studies, despite the fact that multiple

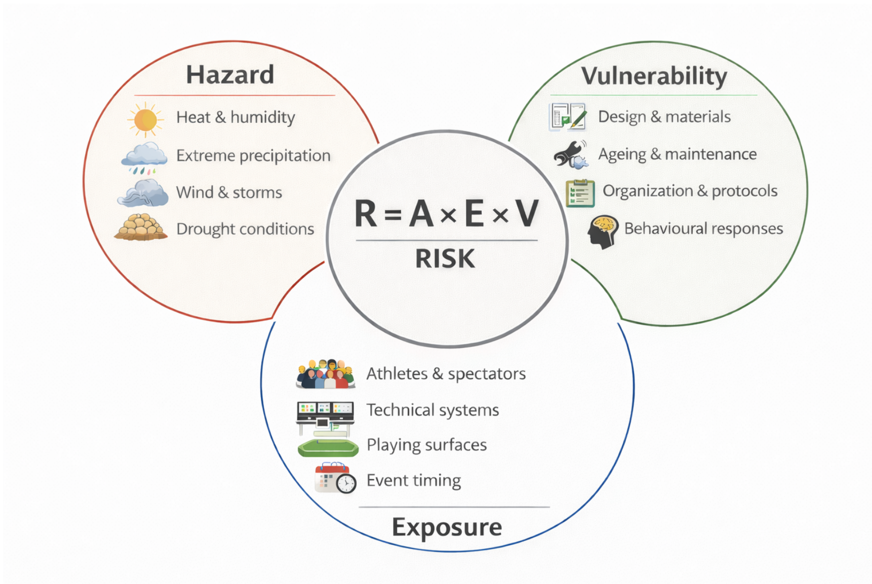

Figure 3: Conceptual representation of the hazard–exposure–vulnerability framework adapted to stadium environments, synthesising the main climate-sensitive risk dimensions identified in the scoping review.

contributions in our corpus already document isolated components corresponding to hazards (A), exposure (E) or vulnerability (V), as synthesised in Figure 3.

Several studies explicitly quantify hazards. For extreme heat, Lindner-Cendrowska et al. (2024) provide a detailed assessment of thermal stress for players at sixteen FIFA World Cup 2026 venues, identifying locations where uncompensable heat loads are likely under present-day climate. Semi-outdoor stadium analyses similarly highlight susceptibility to summer heat waves "due to global warming" (Guo and Sun, 2024). Other contributions address hydro-climatic and coastal hazards, such as Zhu (2020a), who examine flood-control safety and environmental risks for stadiums in marine climates.

Elements of exposure are also documented, although rarely conceptualised as such. Player exposure to high thermal loads is central in the World Cup 2026 assessment (Lindner-Cendrowska et al., 2024), whereas spectator exposure is the core focus of semi-outdoor comfort studies (Guo and Sun, 2024). Operational studies further describe exposure patterns associated with occupancy, match duration or event scheduling, implicitly revealing temporal dynamics of exposure that are almost never integrated into risk analyses.

Dimensions of vulnerability emerge particularly from engineering, architectural and operational work. Thermal-performance optimisation studies demonstrate how canopy geometry, roof design or ventilation configuration significantly modify stadium sensitivity to hot ambient conditions (Zhang et al., 2023). Flood-related vulnerability is highlighted in coastal settings (Zhu, 2020a). Organisational vulnerability appears indirectly in emergency-care studies: for example, Liu et al. (2024) show how heat and heat index increase medical demand, placing additional stress on on-site health services during matches.

Yet, despite the presence of these components, the literature overwhelmingly treats them in isolation. Heat stress, precipitation, wind loads, material ageing, cooling-energy demand or crowd-related health risks are examined as separate problems, often under present-day climate and rarely within a unified analytical structure capable of capturing interactions or cascading dynamics. This fragmentation makes it difficult to assess compound situations—such as the concurrence of extreme heat, high occupancy and elevated cooling demand—or to understand how technical failures and human responses may combine during adverse climatic events.

The A×E×V framework therefore provides a coherent conceptual structure for integrating these heterogeneous but complementary contributions. It enables a more systemic interpretation of existing findings, helps identify potential compound and cascading risks, and offers a foundation for future empirical and modelling studies aiming to translate climatic stressors into operational and strategic risk-management insights for stadium environments. Importantly, this adaptation is proposed as a conceptual prototype rather than an operational tool: quantifying A×E×V interactions will require scenario-based climate assessments, indicator calibration and multi-hazard datasets that are largely absent from the current stadium literature.

5. Conclusions

This scoping review demonstrates that many climate-sensitive processes affecting stadiums are already well described in specialised domains, yet almost never analysed as components of an integrated climate-risk system. Thermal stress on athletes and spectators, wind and storm loads on large-span roofs, water scarcity and turf degradation, cooling-energy demand, drainage failures, and mass-gathering medical risks all appear in the literature, but they do so in disciplinary isolation, with heterogeneous methods and almost no cross-domain articulation. As a result, the existing evidence base provides valuable technical detail but remains poorly suited to informing climate-resilient planning and operation of stadium infrastructures.

Explicit treatment of climate change is rare. A small number of studies quantify future heat-stress conditions for specific tournaments or note the heightened susceptibility of semi-outdoor stadiums to heat waves, while others implicitly touch on adaptation through cooling-system design, reclaimed-water use, or flood-protection measures. Yet, most analyses treat climate as a static boundary condition. Almost none examine how hazard patterns will evolve over the service life of stadiums, nor how concurrent stressors—extreme heat, high occupancy, elevated cooling demand, and pressure on emergency services—might interact to produce compound or cascading risks.

A particularly significant omission concerns heat-related behavioural and health risks. Although extensive evidence from psychology, criminology and environmental social science links elevated temperatures to irritability, aggression and conflict, no stadium-focused study examines how thermal conditions affect crowd dynamics, compliance with safety protocols or escalation potential. Existing medical case studies show that heat and humidity already increase on-site medical demand, but they stop short of framing these patterns within a climate-change trajectory. In parallel, economic analyses indicate that local development gains from stadiums and sport events are often limited and highly variable, and that diversified portfolios of smaller events may be more resilient than dependence on a few climate-sensitive mega-events. Together, these insights suggest that stadiums function as service archipelagos operating under shifting climatic and socio-economic stressors, rather than as isolated match-day engines—yet this perspective remains underdeveloped.

The hazard–exposure–vulnerability (A×E×V) framework provides a coherent structure for connecting these fragmented insights. Many contributions already quantify at least one component: climatic or hydrometeorological hazards (A), the exposure of players, spectators, surfaces or systems (E), or multiple dimensions of vulnerability (V) linked to design, ageing, maintenance, emergency organisation, or behavioural sensitivity. What is missing is the integration of these components into a unified analytical model capable of representing interactions, feedbacks and cascading effects under a warming and more variable climate. Our proposed adaptation of the A×E×V framework for stadium environments is therefore not a new theory, but a means to render existing knowledge commensurable, interpretable and operational for risk management.

Several priorities emerge. First, future research should explicitly incorporate climate projections, assessing how the frequency, intensity and co-occurrence of relevant hazards will change over planning horizons typical of major sport infrastructures. Second, behavioural and organisational vulnerabilities—particularly heat-related crowd responses and the robustness of emergency and evacuation protocols under climatic stress—require dedicated empirical investigation. Third, economic and governance analyses should move beyond static impact assessments and examine how event portfolios, operational models and regulatory contexts shape the resilience of stadiums to climatic shocks and long-term trends. Finally, operationalising an A×E×V approach will require cross-disciplinary collaboration, multi-hazard datasets and scenario-based modelling efforts that are currently lacking.

This review has limitations: it relies on Web of Science, uses keyword-based queries, and focuses on peer-reviewed publications, thereby omitting some technical and practitioner literature. These constraints imply that our synthesis should be read as a conservative depiction of academic knowledge rather than a comprehensive survey of practice. Nonetheless, the overarching conclusion is clear. Current research offers numerous detailed insights into isolated climate-sensitive processes, but systematically underestimates how climate change will amplify, interact and reshape these risks. Developing integrated, climate-informed approaches is essential if stadiums are to remain safe, functional and socially valuable infrastructures in a warming and increasingly volatile climate.

Acknowledgements

The author carried out all aspects of this study independently. No external assistance or institutional support was involved.

Funding

No external funding was received for this research.

Data availability

All data underlying this review consist of bibliographic records retrieved from the Web of Science Core Collection using the ten stadium-focused queries reported in Table 1. The full set of queries, together with the raw WoS export files used for screening, is openly available at Zenodo: DOI:10.5281/zenodo.18380573

Declaration of competing interest

The author declares no competing financial or personal interests. This work was conducted independently within a non-profit association, without commercial sponsors, institutional mandates or contractual obligations.

CRediT authorship contribution statement

DD: Conceptualization; Methodology; Data curation; Investigation; Formal analysis; Writing – original draft; Visualization. **TL**: Investigation; Validation; Writing – review & editing.

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