NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

QUALITY IN SPORT

eISSN 2450-3118 · Open Access · Peer-reviewed

apcz.umk.pl/QS Nicolaus Copernicus University in Toruń



GOC, Artur, DRZEWIECKA, Julia, LASKOWSKA, Karolina, JASIELSKA , Lidia, DĄBEK, Karolina, GARBACZ, Katarzyna, WICZUK, Natalia, SIWKO, Michał, KANADYS, Szymon and SATŁAWSKA, Kamila. Hydration and Nutritional Strategies for Endurance Exercise in the Heat: Differential Effects on Thermoregulation, Exertional Heat Illness Risk, and Performance — A Narrative Review. Quality in Sport. 2026.78.76556. https://doi.org/10.12775/QS.2026.78.76556

ARTICLE TIMELINE

Received: 08.10.2026.
Accepted: 15.10.2026.
Published: 07.11.2026.

INDEXING & EVALUATION

MEiN points: 20 Unique ID: 201398
Disciplines: Economics & Finance; Management & Quality Sciences

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024 No. 32553. Unique Journal Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).

Punkty Ministerialne z 2019 — aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

© The Authors 2026. This article is published with open access under the License Open Journal Systems of Nicolaus Copernicus University in Toruń, Poland. Open Access: This article is distributed under the terms of the Creative Commons Attribution Non-commercial Share Alike License (http://creativecommons.org/licenses/by-nc-sa/4.0/), which permits unrestricted, non-commercial use, distribution, and reproduction in any medium, provided the work is properly cited. The authors declare no conflict of interest regarding the publication of this paper.

Hydration and Nutritional Strategies for Endurance Exercise in the Heat: Differential Effects on Thermoregulation, Exertional Heat Illness Risk, and Performance — A Narrative Review

Artur Goc[1], Julia Drzewiecka[1], Karolina Laskowska[2], Lidia Jasielska[1], Karolina Dąbek[1], Katarzyna Garbacz[1], Natalia Wiczuk[1], Michał Siwko[1], Szymon Kanadys[1], Kamila Satławska[1]

Artur Goc — ORCID: https://orcid.org/0009-0005-1184-0747; E-mail: arturrr1080@gmail.com
Julia Drzewiecka — ORCID: https://orcid.org/0009-0000-9656-9530; E-mail: juliadrzewiecka7@gmail.com
Karolina Laskowska — ORCID: https://orcid.org/0009-0004-8516-8132; E-mail: karolina.laskowska555@gmail.com
Lidia Jasielska — ORCID: https://orcid.org/0009-0005-7544-1606; E-mail: lidiajasielska1215@gmail.com
Karolina Dąbek — ORCID: https://orcid.org/0009-0009-6069-8539; E-mail: karolinadabek02@gmail.com
Katarzyna Garbacz — ORCID: https://orcid.org/0009-0000-8228-7671; E-mail: kgar7777@gmail.com

Natalia Wiczuk — ORCID: https://orcid.org/0009-0000-4228-4169; E-mail: nwiczuk@gmail.com
Michał Siwko — ORCID: https://orcid.org/0009-0002-1870-3989; E-mail: mich.siwko@gmail.com
Szymon Kanadys — ORCID: https://orcid.org/0009-0001-1723-233X; E-mail: szymonkanadys@gmail.com
Kamila Satławska — ORCID: https://orcid.org/0009-0001-4170-419X; E-mail: kamilasatlawska@gmail.com
Affiliations:
[1] Faculty of Medicine, Medical University of Lublin, Aleje Racławickie 1, 20-059 Lublin, Poland
[2] Faculty of Medicine, Medical University of Warsaw, 61 Żwirki i Wigury Street, 02-091 Warsaw, Poland
Corresponding author: Artur Goc; e-mail: arturrr1080@gmail.com

Abstract

Background. Endurance exercise in the heat increases physiological strain and may contribute to exertional heat illness (EHI), but physiological, performance and clinical outcomes are often conflated.
Aim. To compare hydration and nutritional strategies according to their effects on thermoregulation, direct EHI outcomes and endurance performance.
Material and methods. PubMed/MEDLINE was searched through 8 October 2026. Human studies and evidence syntheses were reviewed narratively, with confidence judged separately for each intervention-outcome pair.
Results. Euhydration and individualized drinking support fluid balance, while overdrinking increases exercise-associated hyponatraemia risk. Hyperhydration and internal cooling may provide small, context-dependent performance benefits; carbohydrate is primarily a fuelling strategy. Caffeine may slightly increase thermal strain, menthol mainly alters thermal sensation, and taurine remains experimental. Direct EHI-event evidence is scarce. One observational cohort associated a multicomponent cooling and fluid programme with fewer heat-related medical encounters but could not isolate individual effects.
Conclusions. Strategies should be individualized, rehearsed and integrated with heat acclimation, pacing, environmental controls and emergency planning. Surrogate or performance benefits do not prove EHI prevention.

Key words: heat stress; endurance exercise; hydration; nutrition; exertional heat illness; thermoregulation; performance

1. Introduction

Endurance exercise performed in hot conditions places a large and sustained demand on heat dissipation. Most metabolic energy released during exercise becomes heat, and the capacity to transfer that heat to the environment falls as air temperature and humidity increase. Skin blood flow and sweating therefore assume greater importance, while the same circulation must continue to perfuse active muscle. Progressive fluid loss can reduce plasma volume and increase cardiovascular and perceptual strain, particularly during prolonged, high-intensity exercise.

These responses can impair endurance performance even when they do not progress to clinical heat illness [1,2].

Exertional heat illness (EHI) comprises clinically distinct conditions rather than a single continuum defined by dehydration or core temperature alone. Exertional heat stroke (EHS) is characterized principally by acute central nervous system dysfunction in the setting of exercise-induced hyperthermia, whereas heat exhaustion lacks the profound neurological dysfunction of EHS. The epidemiological burden varies widely across sports, event formats and surveillance systems. In a systematic review of 62 studies, rates ranged from 0.01 to 4.19 cases per 1000 athletic-exposures and from 0.01 to 54.54 cases per 100 participants, with the highest participant-based rates reported in endurance events [3]. Hydration remains relevant because hypohydration can magnify cardiovascular and thermal strain, but EHS can occur without a documented large fluid deficit, and adequate hydration does not guarantee prevention [4]. A complementary systematic review of 42 primary studies found that EHI was better explained by interacting lifestyle, health, work and environmental factors than by any single isolated factor [5].

Athletes and practitioners use several nutritional approaches to manage these demands. Beginning exercise euhydrated, matching drinking more closely to event demands and using sodium when substantial fluid replacement is appropriate can support fluid balance. Pre-exercise hyperhydration seeks to expand body-water stores, carbohydrate provision supports fuel availability, and cold fluids or ice slurry provide internal cooling. Caffeine, taurine, menthol, creatine and other supplements have also been proposed to improve performance, heat tolerance or thermal perception [6,7,8]. Each strategy acts through a different pathway, however, and may affect fluid balance, core temperature, sweating, perception and performance in different directions.

These outcomes require separate interpretation. A small reduction in core temperature in a laboratory trial does not show that fewer athletes will develop EHI. Greater sweating can promote evaporation in dry, well-ventilated conditions but may only increase fluid loss when sweat cannot evaporate. Menthol can improve thermal sensation without reducing body heat storage, and an improvement in cycling time to exhaustion may not transfer to a self-paced road race. An intervention may still help performance or comfort when clinical events are too rare to study. Conclusions must therefore remain tied to the measured outcome, design, environment and population.

Previous reviews and consensus documents have addressed exercise thermophysiology, nutrition in hot environments, EHS-related nutritional considerations and the efficacy of individual cooling or supplementation strategies [1,4,6,9]. A recent Quality in Sport review focused on recognition and emergency cooling after EHS is suspected [10]. The present review has a different purpose: prevention and preparation before and during endurance exercise, with emergency treatment discussed only to define safety boundaries. Its central contribution is an outcome-specific comparison of interventions rather than a catalogue of products.

Accordingly, this narrative review critically evaluates hydration and nutritional strategies for endurance exercise in the heat by separating their effects on thermoregulation, direct EHI outcomes and endurance performance. It asks which strategies meaningfully alter physiological heat strain, which have evidence from diagnosed EHI events or heat-related medical encounters, which improve performance, and how sex, acclimation, exercise mode, environmental conditions and event logistics modify their application. The final synthesis translates those distinctions into practical recommendations with outcome-specific confidence ratings.

2. Materials and methods

2.1. Review design and scope

This narrative review used a structured literature-search and evidence-appraisal approach to examine hydration and nutritional strategies for endurance exercise performed in the heat. The review was designed to integrate mechanistic, laboratory, field and clinical evidence while preserving distinctions between outcomes that are frequently conflated in this literature. The review was not registered prospectively and was not intended to constitute a systematic review or meta-analysis.

Three outcome domains were defined a priori: thermoregulation, endurance performance and exertional heat illness (EHI). Thermoregulatory outcomes included core and skin temperature, sweat responses, heat storage, cardiovascular strain and thermal perception. Performance outcomes included time to exhaustion, time-trial performance, total work and field-based performance measures. Direct EHI outcomes were restricted to clinically relevant events, including heat-related medical encounters, exercise-associated heat exhaustion, exertional heat stroke, withdrawal attributed to heat illness and related hospital presentation. Physiological or perceptual variables were treated as intermediate or surrogate outcomes rather than direct evidence of EHI prevention.

2.2. Information sources and search strategy

PubMed/MEDLINE was used as the primary bibliographic database. Searches were conducted between 24 September and 8 October 2026 and were last updated on 8 October 2026. Search strings combined controlled vocabulary and title/abstract terms for athletes or endurance exercise; heat exposure or hot environments; and hydration, fluid intake, sodium, electrolytes, carbohydrate, hyperhydration, glycerol, cold fluids, ice slurry, caffeine, taurine, menthol, creatine and other potentially relevant nutritional strategies. Additional search blocks targeted exertional heat illness, exertional heat stroke, heat exhaustion, exercise-associated hyponatraemia, heat-related medical encounters, female participants, menstrual-cycle phase and hormonal contraception.

Broad searches were supplemented by focused searches for systematic reviews, meta-analyses, consensus statements, position statements and primary trials addressing individual interventions. The core search logic combined (athlete* OR endurance OR exercise OR running OR cycling OR triathlon) AND (heat OR hot environment OR heat stress) AND intervention terms for hydration, sodium, carbohydrate, internal cooling or supplements, with outcome terms for thermoregulation, performance or heat illness. No date restriction was applied to targeted searches for direct EHI outcomes or pre-exercise hyperhydration when older evidence remained clinically relevant; broader intervention searches generally emphasized literature published from 2000 onwards. No language restriction was applied at the search stage, although the detailed synthesis was limited to publications available in English. Reference lists of eligible reviews, consensus documents and key primary studies were examined to identify additional publications and to check whether important intervention-specific evidence had been missed.

2.3. Eligibility criteria

Eligible sources examined human participants undertaking endurance or prolonged exercise in hot or thermally stressful conditions and evaluated a hydration, fluid-balance, nutritional, supplementation or internal-cooling strategy relevant to the review question. Randomized and non-randomized trials, crossover studies, prospective and retrospective field studies, systematic reviews, meta-analyses, consensus statements and position statements were considered. Studies involving recreationally active, trained or elite participants were eligible. Evidence from military or occupational populations was included only when the exercise model and heat

exposure were sufficiently relevant to endurance sport or when the study contributed direct clinical EHI information.
Studies were excluded when they were limited to animals, in-vitro models, passive heat exposure without an exercise component or interventions unrelated to hydration, nutrition or internal cooling. Papers focused solely on recognition or emergency treatment after suspected exertional heat stroke were used only to define the clinical boundary of the review and were not included as evidence for preventive nutritional strategies. Studies conducted outside the heat were used only when necessary to explain an established mechanism or safety issue and were not treated as direct heat-specific efficacy evidence. Abstract-only records could inform evidence mapping, but detailed numerical claims were preferentially based on verified full texts.

2.4. Study selection and data extraction

Search results were imported into Zotero and organized in intervention-specific collections. Records retrieved by overlapping searches were treated as a single publication. Because this was a narrative rather than systematic review, the broad overlapping result sets were not treated as one exhaustively screened corpus. Candidate records were prioritized purposively according to relevance to the predefined population, exposure, intervention and outcome domains; priority was given to recent systematic reviews or meta-analyses, consensus or position statements, primary trials that supplied intervention-specific estimates, field studies reporting direct EHI outcomes, and studies addressing women or elite athletes. Potentially relevant full texts were then assessed. Records were not combined into a single PRISMA-style denominator, and no claim of systematic-review completeness is made.
For each included source, the following information was extracted when available: study design, sample size, sex, training status, heat-acclimation status, environmental temperature and humidity, exercise mode and duration, intervention and comparator, dose and timing, fluid availability, thermoregulatory outcomes, performance outcomes, direct EHI outcomes, adverse effects and major limitations. Numerical claims were checked against the full publication whenever it was available. If only an abstract was available, only results explicitly reported in that abstract were used. Particular attention was paid to whether an apparent benefit reflected a time-to-exhaustion protocol, a time trial, a laboratory surrogate or a clinical event.

2.5. Narrative synthesis and confidence assessment

Evidence was synthesized by strategy and then compared across the three outcome domains. Meta-analytic estimates from eligible published reviews were used when available; no new statistical pooling was performed. Multicomponent interventions were interpreted as integrated packages unless the study design isolated the contribution of individual components. Findings from cycling time-to-exhaustion protocols were not assumed to translate directly to self-paced running, time-trial or competition performance.
Confidence was judged separately for thermoregulation, performance and direct EHI outcomes as high, moderate, low or very low. The narrative judgment considered study design, risk of bias, sample size and precision, consistency between studies, directness of the measured outcome and applicability to endurance athletes in real-world heat. High confidence required consistent direct evidence or strong guideline-level support; moderate confidence indicated reasonably consistent evidence with important limitations; and low or very low confidence reflected sparse, imprecise, inconsistent, indirect or predominantly mechanistic evidence. These categories were used to make the basis of recommendations explicit and should not be interpreted as a formal GRADE assessment.

3. Physiological basis and outcome framework

3.1. Heat balance and thermoregulatory strain

During endurance exercise, most of the energy released by skeletal-muscle metabolism appears as heat rather than external work. Body heat storage therefore reflects the balance between metabolic heat production and heat exchange with the environment through evaporation, convection, radiation and conduction. When air temperature approaches or exceeds skin temperature, dry heat loss becomes progressively restricted and may reverse into environmental heat gain. Evaporation of sweat then becomes the principal avenue for heat dissipation. Its effectiveness depends not only on sweat production but also on ambient humidity, air movement, clothing and the proportion of sweat that evaporates rather than drips from the skin [1]. Consequently, a high sweat rate does not necessarily indicate effective cooling, particularly in humid or poorly ventilated conditions.

Thermoregulation also imposes a circulatory demand. Cutaneous vasodilatation increases skin blood flow to transfer heat from the body core to the surface, while exercising muscle simultaneously requires substantial perfusion. Sweating reduces total body water and, when losses are not sufficiently replaced, contracts plasma volume and raises extracellular osmolality. The resulting combination of reduced central blood volume, greater skin blood flow and continued muscular demand lowers ventricular filling and stroke volume. Heart rate rises to defend cardiac output, but cardiovascular strain and perceived effort progressively increase. Hypohydration can also shift the core-temperature thresholds for vasodilatation and sweating and reduce the sensitivity of these responses, thereby accelerating heat storage under otherwise comparable conditions [1,2].

These mechanisms explain why meaningful hypohydration may worsen thermal and cardiovascular strain, but they do not support a universal fluid-replacement target. Sweat rate, sweat sodium concentration, gastrointestinal absorption, opportunities to drink, exercise intensity, body size, acclimation and environmental conditions differ markedly between athletes and events. Moreover, the physiological consequences of a given percentage of body-mass loss vary with exercise mode, duration and the degree to which the athlete can regulate pace. Fluid strategies should therefore be interpreted as methods of managing an interacting heat-balance and circulatory problem, not as attempts to normalize one isolated measurement at all costs.

3.2. Exertional heat illness and scope boundaries

Exertional heat illness is an umbrella term covering clinically distinct disorders that occur in association with physical exertion and heat stress. For the purposes of this review, exercise-associated heat exhaustion denotes an inability to continue exercise accompanied by symptoms and signs compatible with excessive heat strain but without the central nervous system dysfunction that characterizes exertional heat stroke. Exertional heat stroke is a medical emergency defined principally by acute central nervous system dysfunction in the context of exercise-induced hyperthermia; a deep body temperature above approximately 40°C is common, but temperature should be interpreted with the clinical presentation and the timing and method of measurement [2,4]. Heat syncope, heat cramps and other heat-related presentations may coexist with dehydration or electrolyte disturbance but are not interchangeable diagnoses.

The epidemiological burden varies markedly by sport and by the denominator used. A systematic review of 62 studies reported EHI rates ranging from 0.01 to 4.19 cases per 1000 athletic-exposures and from 0.01 to 54.54 cases per 100 participants; endurance events, particularly running, cycling and adventure racing, produced the highest participant-based rates. Across 23 studies reporting EHI alongside other injuries or medical encounters, EHI accounted

for an average of 6.6% of all recorded conditions [3]. These figures establish the relevance of EHI to endurance sport, but they should not be treated as a single pooled risk estimate because event type, exposure definition, diagnostic criteria, climate, participant characteristics and surveillance quality differed substantially.

The transition from tolerable heat strain to EHI is not explained by hydration status alone. Environmental heat and humidity, solar radiation, metabolic rate, clothing or protective equipment, insufficient heat acclimation, recent illness, sleep and recovery, medication use, individual susceptibility and the behavioural decision to maintain pace despite warning symptoms may all contribute. Dehydration can amplify cardiovascular and thermal strain and may lower tolerance, yet EHS can occur in apparently well-hydrated individuals and in environmental conditions that are not exceptionally hot. Conversely, many athletes complete hot-weather endurance events with body-mass losses and elevated core temperatures without developing EHI. Adequate hydration must therefore be presented as one component of risk management rather than a guarantee of prevention [4,5].

This review addresses prevention before and during endurance exercise. Recognition, rectal-temperature assessment, emergency cooling and return-to-play management are clinically essential but fall outside its primary scope. They are discussed only where necessary to distinguish preventive strategies from treatment. In particular, consuming fluid, sodium, carbohydrate or a cooling supplement must never delay established emergency procedures when EHS is suspected. This boundary also avoids duplicating the recent Quality in Sport review devoted specifically to EHS recognition and cooling protocols [10].

3.3. Why thermoregulation, EHI risk and performance must be evaluated separately

Thermoregulatory, clinical and performance outcomes are related but not interchangeable. Core and skin temperature, sweat rate, plasma-volume change, heart rate and thermal perception help explain physiological or perceptual strain. A modest change in any one measure does not establish prevention of heat exhaustion or EHS. Its meaning also depends on context: additional sweating may assist evaporation in dry, well-ventilated conditions but increase fluid loss when evaporation is constrained, while menthol can improve thermal sensation without reducing body heat storage.

Performance findings also depend on the test. Time-to-exhaustion protocols are sensitive to changes in tolerance and often produce larger effects than self-paced time trials. Total-work tests and field competition add different pacing, aerodynamic, biomechanical and behavioural constraints. Perception or substrate availability may improve performance without lowering core temperature; conversely, a small reduction in thermal strain may not improve a short event or may be offset by added fluid mass. This review therefore distinguishes time to exhaustion, time-trial performance, total work and field outcomes.

Direct EHI evidence requires diagnosed heat illness, heat-related medical encounters, heat-related withdrawal, hospital presentation or EHS. These events are uncommon, and trials cannot ethically expose participants to severe illness; most intervention studies therefore report intermediate outcomes. Physiological plausibility and better performance may support a preventive rationale, but they do not demonstrate lower EHI incidence. Confidence is consequently judged separately for thermoregulation, endurance performance and direct EHI outcomes.

4. Hydration and fluid-balance strategies

4.1. Starting exercise euhydrated

Beginning prolonged exercise with a substantial fluid deficit reduces the margin available for subsequent sweat loss. As hypohydration progresses, the reduction in plasma volume increases

cardiovascular strain, while hyperosmolality and hypovolaemia can delay cutaneous vasodilation and sweating and thereby increase heat storage. These effects become more consequential as exercise duration, intensity and environmental heat increase. The practical objective before an event is therefore to correct a meaningful pre-existing deficit and begin in a normally hydrated state, rather than to create the largest possible fluid reserve [1,6,7].

Euhydration should not, however, be presented as a guarantee against EHI. A military case series summarized by Lee et al. reported that dehydration was not identified as a contributing factor in 83% of EHS cases, and the review concluded that the role of hydration in EHS prevention remained unclear [4]. This does not make hydration irrelevant; it shows that EHS is multifactorial and can occur without a documented large fluid deficit. Consequently, pre-event practice should focus on avoiding a known deficit, while heat acclimation, appropriate pacing, environmental monitoring and early symptom recognition remain independent safeguards [1,2].

4.2. Individualized drinking during exercise

A single universal drinking rate is not defensible because sweat loss varies widely between athletes and within the same athlete across pace, heat, humidity, clothing and acclimation state. A useful starting estimate is obtained from the change in body mass during a representative training session, adjusted for fluid consumed and urine produced. Repeating this measurement under conditions resembling the target event is more informative than relying on a generic value. The resulting plan must also account for drink availability, expected duration, gastrointestinal tolerance and the fact that fluid ingested during competition is rarely intended to replace every millilitre of sweat [1,7,8].

The physiological target is a workable range between excessive fluid deficit and positive fluid balance, not exact replacement at all costs. Larger deficits tend to increase heart rate, thermal strain and perceived exertion, particularly during prolonged, high-intensity exercise in the heat, but the relationship with performance is modified by study design, airflow, familiarity with dehydration and exercise mode. Equally, rapid replacement can exceed gastrointestinal absorption or tolerance and may promote overdrinking. Individualization therefore means using sweat-rate information to define plausible needs, then testing the plan in training and adjusting it to thirst, tolerance, aid-station logistics and observed body-mass change [1,7].

Direct EHI-event evidence for individualized fluid replacement remains limited. A 2026 non-randomized field study compared a structured graded cooling and fluid-replacement programme with conventional care across four hot-humid endurance events. After within-event propensity-score matching, heat-related medical encounters occurred in 10 of 116 programme participants and 20 of 116 controls (conditional OR 0.41, 95% CI 0.17-0.99), alongside a 0.50°C lower post-race core temperature and better preservation of race time [11]. The programme combined pre-race ice slurry, external cooling, individualized carbohydrate-electrolyte fluid provision and immediate post-finish cooling; no EHS occurred, the number of medical events was small, and treatment allocation was not randomized. The finding therefore supports feasibility and further evaluation of an integrated event-level package, but it cannot establish that individualized drinking alone prevents EHI.

4.3. Planned drinking and drinking to thirst

Planned drinking and drinking to thirst are better treated as context-dependent tools than as mutually exclusive doctrines. In Kenefick's review, planned drinking was most applicable to exercise lasting longer than approximately 90 min, especially when it was intense, performed in the heat, associated with high sweat rates or combined with a defined carbohydrate-delivery target. In these settings, a plan based on measured sweat loss may limit a deficit that thirst alone does not fully replace. Thirst can be blunted during exercise and may be relieved before

complete rehydration, which explains why ad libitum intake sometimes replaces only part of the loss [7].

Conversely, thirst-guided drinking is often sufficient for shorter or lower-intensity activity, cooler conditions and many long events in which pace is modest and frequent access to fluid is available. It also provides an important defence against overconsumption. The Wilderness Medical Society guideline recommends reliance on innate thirst for most participants because this approach generally limits both severe dehydration and overhydration, while acknowledging that unusually rapid losses may require a more deliberate strategy [12]. Neither approach justifies forcing fluid. A simple safety boundary common to both is that an athlete should not deliberately drink enough to gain body mass during exercise [7,12].

Event context should determine the degree of planning. A high-sweat-rate athlete racing hard for several hours in the heat has a stronger rationale for a rehearsed fluid-intake range than an athlete completing a short, low-intensity session. Even then, thirst, gastrointestinal symptoms, changes in weather or pace, and access to aid stations may require real-time adjustment rather than adherence to an inflexible hourly volume.

4.4. Sodium and electrolyte replacement

Sodium should be considered together with water balance rather than as an independent protective supplement. During exercise, sodium in food or drink may support fluid retention, preserve beverage palatability, influence thirst and help deliver carbohydrate. Its relevance increases when exercise is prolonged, fluid replacement is substantial and sweat sodium losses are high. Nevertheless, the most recent focused review found no evidence that athletes require routine daily sodium supplementation outside specific exercise-related needs, and concluded that sodium intake during exercise does not appear to improve performance unless it produces a more appropriate fluid intake [8].

Attempting to replace a calculated sweat-sodium loss gram for gram is not automatically necessary. Sweat testing itself is method-sensitive, sodium losses vary, and renal conservation continues after exercise. McCubbin [8] proposed that replacement should complement the intended fluid balance: when replacing a large proportion of fluid loss is both desirable and feasible, sodium can help limit a fall in plasma sodium; when much less fluid is required, the value of matching sweat sodium is smaller. Evidence does not support presenting sodium capsules or highly concentrated drinks as universal EHI-prevention measures, and excessive or poorly tolerated doses can add gastrointestinal burden.

Sodium also does not neutralize the risk created by excessive water intake. Exercise-associated hyponatraemia (EAH) primarily reflects a relative excess of water in relation to exchangeable body solute, commonly combined with non-osmotic arginine-vasopressin activity. Supplemental sodium may modify the fall in plasma sodium in selected circumstances, but it cannot make unrestricted drinking safe. Practical advice should therefore begin with an appropriate fluid strategy; sodium concentration and delivery method are secondary, individualized decisions based on duration, expected fluid intake, sweat characteristics, diet and tolerance [8,12].

4.5. Pre-exercise hyperhydration

Pre-exercise hyperhydration deliberately expands body-water stores before exercise, most commonly by co-ingesting a large fluid volume with an osmotic agent such as sodium or glycerol. Water alone is poorly retained because the fall in osmolality suppresses vasopressin and increases urine production. Across 38 studies in a 2023 systematic review, hyperhydration increased plasma volume by 3.5-12.6% in ten studies; during constant-work exercise, nine studies reported a 3-11 beats·min^{-1} lower mean heart rate and eight reported a 0.1-0.8°C lower mean core temperature. However, protocols, exercise models and environments were

heterogeneous, 90% of participants in performance studies were male, and only a small number of studies used female participants [13].

The performance signal is modest and depends on the endpoint. A subsequent meta-analysis found small-to-moderate benefits for time to exhaustion (Hedges' g=0.31, 95% CI 0.13-0.50) and time-trial performance (g=0.25, 95% CI 0.002-0.51), but not for total-work tests [14]. It found no overall effect on heart rate, body temperature, perceived exertion or thermal comfort at the analysed endpoints. A meta-regression suggested lower post-performance-task body temperature with sodium than glycerol, but this isolated result arose within a relatively homogeneous evidence base and should not be treated as proof of superiority. These pooled results favour a possible performance benefit while weakening any claim that hyperhydration consistently improves thermoregulation.

Female-specific primary evidence is beginning to emerge but remains limited. In a randomized crossover trial of 12 female cyclists or triathletes, participants consumed 30 $mL \cdot kg^{-1}$ fat-free mass of fluid containing sodium chloride (7.5 $g \cdot L^{-1}$) or a sucrose placebo 2 h before 75 min of cycling at 60% of peak oxygen uptake followed by a 200-kJ time trial in 34°C and 60% relative humidity. Sodium hyperhydration increased pre-exercise fluid retention by 509 mL (95% CI 349-669) and reduced urine volume by 107.4 mL; body-mass loss was 0.20 percentage points lower after steady-state exercise and 0.15 percentage points lower after the time trial [15]. No consistent main effect of menstrual-cycle phase was observed. Exploratory phase-specific findings in this small study do not justify universal phase-based prescriptions, and the trial assessed hydration responses rather than clinical EHI.

Gastrointestinal tolerance is a central practical limitation. Gastrointestinal symptoms were reported in 26 of the studies reviewed by Jardine et al. [13], with severity apparently affected by the agent, dose and ingestion rate. The added pre-event body mass may also offset benefit in weight-bearing exercise, and evidence in elite athletes, women and running is sparse. No trial base demonstrates that sodium- or glycerol-induced hyperhydration prevents clinical EHI. Hyperhydration is therefore best classified as an optional, rehearsed performance strategy for selected long, hot events in which drinking opportunities may be limited—not a routine safety requirement and not a substitute for acclimation, pacing or an appropriate during-exercise plan.

4.6. Overdrinking and exercise-associated hyponatraemia

Avoidance of overdrinking is the clearest safety conclusion in this section. EAH is defined as a serum or plasma sodium concentration below 135 $mmol \cdot L^{-1}$ during or within 24 h after prolonged physical activity. The principal modifiable risk is fluid consumption in excess of losses, particularly when continued vasopressin secretion limits free-water excretion. Body-mass gain during exercise is therefore a practical warning sign of positive fluid balance, although diagnosis requires clinical assessment and, where possible, sodium measurement [12].

EAH and EHI are distinct disorders but may present with overlapping nonspecific features, including weakness, headache, nausea, vomiting, dizziness, confusion or collapse. Treating every collapsed athlete as dehydrated and automatically providing hypotonic oral fluid or rapid isotonic intravenous fluid can worsen EAH. Bennett et al. [12] therefore emphasized inclusion of EAH in the differential diagnosis of heat exhaustion and EHS. This review does not address acute treatment protocols, but the preventive implication is direct: athletes and event staff should avoid forced drinking, recognize weight gain or bloating as warning features and understand that sodium intake does not justify drinking beyond need.

The evidence supports an individualized sequence: start without a meaningful fluid deficit, estimate losses under representative conditions, choose thirst-guided or more planned drinking according to event demands, use sodium only to support the fluid plan, and avoid positive fluid balance. These recommendations are better supported for managing physiological strain and preventing EAH than for preventing EHS.

5. Nutritional and internal-cooling strategies

5.1. Carbohydrate intake

Carbohydrate intake during prolonged exercise is primarily a fuelling strategy, not a cooling intervention. Heat stress can increase reliance on endogenous carbohydrate and may alter gastrointestinal function, creating a plausible rationale for carbohydrate provision; however, this rationale does not establish that more carbohydrate is required in the heat. The most directly relevant systematic review identified only nine randomized crossover studies of continuous endurance exercise lasting approximately 50-152 min in ambient temperatures above 23°C. Ingestion rates varied markedly, from 14 to 140 $g \cdot h^{-1}$, and the interventions, pre-exercise meals, exercise protocols and environmental conditions were heterogeneous [16].

The performance findings were mixed. Five studies reported statistically significant improvements, comprising 13.4-19.3% increases in time to exhaustion and 3.3-12.7% improvements in time-trial outcomes, whereas four studies found no significant benefit. Importantly, three of the five time-trial studies found no effect, and the larger improvements were often observed in time-to-exhaustion protocols, which have lower ecological validity and greater variability than self-paced trials. Salame et al. [16] concluded that the available trials do not show a consistent performance benefit from carbohydrate provision under hot conditions. The evidence supports retaining carbohydrate as a potentially useful fuel for sufficiently prolonged exercise, but not presenting it as a heat-specific ergogenic strategy with a predictable effect. The final update search identified a later randomized trial in ten well-trained male cyclists: during a 60-km self-paced cycling trial in the heat, 6% carbohydrate delivered as a beverage or capsules did not improve performance time or post-exercise neuromuscular outcomes compared with placebo [37]. This neutral finding is consistent with the conclusion that carbohydrate should be used for fuelling rather than as a reliably heat-specific ergogenic intervention.

The same review found little evidence of a thermoregulatory benefit. Seven of eight studies that measured rectal or core temperature reported no difference between carbohydrate and placebo, while one reported a higher rectal temperature with carbohydrate. Hydration markers were also generally unchanged: only two studies reported differences, in opposite directions, including greater plasma-volume loss with a 14% carbohydrate drink in one trial. Six of seven studies measuring perceived exertion found no between-condition difference. Accordingly, carbohydrate ingestion cannot be classified as physiological cooling and there are no direct data showing that it reduces clinical EHI events [16].

Gastrointestinal tolerance may determine whether a theoretically appropriate fuelling plan remains beneficial in the heat. Only two of the nine included studies formally assessed gastrointestinal symptoms. A 12% glucose drink supplying approximately 99 $g \cdot h^{-1}$ produced more nausea, fullness and stomach upset than a 6% drink and placebo, while a 16% maltodextrin-fructose drink supplying 90 $g \cdot h^{-1}$ increased fullness compared with water. Conversely, seven studies did not assess gastrointestinal symptoms, limiting interpretation because heat can aggravate gastrointestinal disturbance. The evidence does not justify deriving a new universal carbohydrate target for hot conditions. Athletes should begin adequately fuelled, retain established duration-dependent carbohydrate targets as a starting point, and rehearse the chosen amount, concentration, form and drinking schedule in representative heat. Increasing intake simply because conditions are hotter is not supported; when heat or intensity reduces tolerance, a lower tested intake may be more practical than forcing a target [16].

5.2. Cold fluids and ice slurry

Cold-fluid and ice-slurry ingestion provide internal cooling because energy is required to warm the ingested material to body temperature and, for ice, to complete the phase change from solid

to liquid. Ice therefore provides a larger theoretical heat sink than the same mass of cold water. Internal cooling can be applied before exercise, during exercise or at both time points, and the beverage simultaneously contributes to fluid intake. Its physiological effect must nevertheless be interpreted as part of whole-body heat exchange rather than as a guaranteed reduction in heat storage [1,17].

The largest directly relevant meta-analysis included 47 intervention studies and 486 active participants, of whom only 13.7% were female. Pooled internal-cooling interventions produced a small improvement in time to exhaustion (SMD 0.40, 95% CI 0.13-0.67), with the significant subgroup effect confined to pre-exercise ice or cold-water ingestion (SMD 0.52, 95% CI 0.10-0.95). Evidence for time-trial completion was less certain: the authors reported SMD -0.31 (95% CI -0.60 to -0.02) together with p=0.06 and described the result as borderline; mean power output was also borderline. These differences matter practically: improved exercise tolerance in a fixed-intensity test should not be translated directly into a guaranteed competitive-performance gain [18].

Thermoregulatory effects were statistically detectable but small. Across 35 studies, internal cooling reduced end-exercise core temperature by a trivial standardized effect (SMD -0.19, 95% CI -0.34 to -0.05); only combined pre- and mid-exercise ice or cold-water ingestion produced a significant subgroup reduction (SMD -0.32, 95% CI -0.57 to -0.06). Internal cooling also reduced sweat rate (SMD -0.20, 95% CI -0.34 to -0.06) and thermal sensation (SMD -0.17, 95% CI -0.33 to -0.01), but did not significantly change skin temperature, thermal comfort or blood lactate. Heart rate and perceived exertion showed only borderline pooled effects [18].

A lower sweat rate is not necessarily evidence of superior whole-body cooling. Cold stimulation of abdominal thermoreceptors can suppress sweating; in hot-dry conditions, the resulting reduction in evaporative heat loss may equal or exceed the internal heat absorbed by the drink. Thus, a beverage may feel cooler and transiently lower measured core temperature without producing an equivalent reduction in net heat storage. The balance depends on humidity, air movement, clothing and whether sweat can evaporate. This mechanism is one reason not to describe ice slurry as universally superior to a tolerable cool drink [1,17].

Most protocols have used approximately 500-700 mL, often expressed as about 7.5 $g \cdot kg^{-1}$ and divided into smaller portions before exercise, but the studies covered a much wider dose range and meta-regression did not confirm a clear dose-response relationship. These values should therefore be reported as commonly studied protocols rather than prescriptions. Large volumes can cause fullness, nausea, headache or 'brain freeze', and all fluid must be counted within the athlete's total drinking plan to avoid overconsumption. The strategy should be rehearsed in training, with a temperature, volume and timing the athlete can tolerate; combining pre- and during-exercise ingestion may prolong the cooling exposure, but feasibility will depend on event logistics [1,18].

No included trial programme was designed to determine whether cold fluids or ice slurry alone reduce diagnosed heat exhaustion or EHS. Evidence is therefore moderate for a small improvement in exercise capacity, lower for self-paced performance, and indirect for EHI prevention. Internal cooling can be presented as an optional adjunct for selected hot-weather events, particularly when it can be integrated into an already appropriate hydration and carbohydrate plan. It must not be used to justify a faster pace despite worsening symptoms, and it does not replace heat acclimation, environmental risk management or immediate withdrawal and clinical assessment when EHI is suspected.

6. Supplements and perceptual cooling aids

6.1. Caffeine

Caffeine should be framed as a potential ergogenic aid rather than as a hydration or cooling strategy. The International Society of Sports Nutrition position stand concluded that caffeine can enhance several aspects of performance, most consistently at doses of 3-6 $mg \cdot kg^{-1}$, but also emphasized substantial interindividual variation [19]. Heat-specific evidence is less reassuring. In a meta-analysis centred on approximately 6 $mg \cdot kg^{-1}$ taken 1 h before exercise, the pooled performance estimate was +2.1% (95% CI -0.7% to 4.8%) and therefore not statistically significant, while the rate of core-temperature rise increased by 0.10°C·h^{-1} (95% CI 0.02-0.19). The small evidence base and heterogeneous protocols precluded a firm clinical-safety conclusion [20].

A later randomized crossover trial illustrates why general ergogenic findings should not be transferred uncritically to hot conditions. Twelve caffeine-habituated, non-heat-acclimatized men ingested 5 $mg \cdot kg^{-1}$ caffeine or placebo 60 min before cycling to exhaustion at the gas-exchange threshold in 35°C and 40% relative humidity. Caffeine did not improve time to exhaustion (28.5±8.3 versus 29.9±8.8 min; p=0.251), but increased oxygen uptake by 7.4%, metabolic heat production by 7.9%, whole-body sweat rate by 21% and evaporative heat transfer by 16.5%, reduced estimated skin blood flow by 14.1%, and resulted in a higher mean core temperature (38.09 versus 37.87°C) without a statistically significant difference in the rate of rise (p=0.053) [21]. A broader 2025 meta-analysis similarly reported a small increase in peak core temperature with caffeine (Hedges' g=0.44, 95% CI 0.275-0.603), without a pooled increase in whole-body sweat rate [22].

These data do not demonstrate that caffeine causes EHI: clinical heat-illness events were not measured, and laboratory changes in core temperature cannot be equated with EHS incidence. They do, however, argue against recommending caffeine to improve heat safety. Athletes who already use caffeine for performance should test the lowest effective dose during representative training, account for total caffeine from drinks, gels and supplements, and avoid escalating the dose in hot conditions. A history of adverse symptoms, poor heat tolerance or an unfamiliar competition environment strengthens the case for omission. The certainty of evidence is low-to-moderate for a small adverse thermal effect, variable for performance, and very low for direct EHI risk.

6.2. Taurine

Taurine has shown promising signals, but the evidence remains preliminary. Page et al. [23] studied 11 non-heat-acclimatized men in a double-blind randomized crossover trial. A single 50 $mg \cdot kg^{-1}$ dose in capsules, taken 2 h before cycling at ventilatory-threshold power in 35°C and 40% relative humidity without drinking, increased time to exhaustion from 22.43 to 25.16 min (p=0.040; d=0.70). There was no overall condition effect for core temperature; only the final normalized exercise epoch was lower with taurine (38.1 versus 38.5°C; p=0.049). Taurine also increased local sweating and body-mass loss. The result is compatible with enhanced evaporative cooling, but it arose from a small male sample and a time-to-exhaustion protocol.

Peel et al. [24] tested a longer regimen in 15 participants (12 men and 3 women). Following 50 $mg \cdot kg^{-1} \cdot day^{-1}$ for 8 days, low-intensity treadmill exercise at fixed heat production in 37.5°C was performed first at fixed humidity and then with progressively increasing humidity. Taurine increased whole-body sweat loss by 26.6% during the fixed-humidity phase and 5.1% during the incremental phase, increased local sweat rate by 15.5% and 7.8%, enhanced evaporative heat loss by 27%, reduced calculated heat storage by 72%, and shifted the critical vapour-pressure breakpoint from 21.7 to 25.0 mmHg. This provides mechanistic evidence within one small controlled protocol, not proof of better racing performance or fewer clinical events.

A separate single-blind crossover trial in 12 physical-education students compared taurine, caffeine, their combination and placebo during cycling to exhaustion in 35°C and 65% relative humidity. Mean time to exhaustion was longer in each active condition than with placebo, but only the taurine-versus-placebo comparison was statistically significant (23.89 versus 20.48 min; p=0.03; d=1.24). Taurine also produced the most favourable late-exercise core-temperature response, whereas co-ingestion did not provide an additive benefit [25]. The small sample, time-to-exhaustion endpoint and limited participant description constrain generalizability. In the larger thermoregulation meta-analysis, taurine increased whole-body sweating (n=3; Hedges' g=0.79; p=0.006) and lowered peak core temperature (n=3; g=-0.66; p=0.043), but these estimates rested on only three comparisons [22].

A newer double-blind crossover study did not replicate an ergogenic or thermoregulatory benefit of the combined formulation. Ten non-heat-acclimated adults received 5 $mg \cdot kg^{-1}$ caffeine plus 50 $mg \cdot kg^{-1}$ taurine or placebo 1 h before cycling at the gas-exchange threshold in 35°C and 40% relative humidity. Co-ingestion did not improve time to exhaustion (p=0.608) and did not alter core temperature (p=0.699) or whole-body sweat rate (p=0.897), although oxygen consumption, minute ventilation and heat production were higher [26]. This disagreement with Yu et al. [25] makes a general recommendation for caffeine-taurine products untenable.

Naddafha et al. [27] mapped the same small human evidence base in a narrative review and judged taurine promising but context dependent. The review highlighted acute doses near 50 $mg \cdot kg^{-1}$ and short multi-day regimens, possible increases in eccrine sweating and modest reductions in core temperature, while emphasizing heterogeneous protocols, small samples, absence of adequately powered field trials and the possibility that greater sweat loss increases fluid and sodium requirements. Because it is a narrative synthesis rather than independent efficacy evidence, it supports the mechanistic interpretation and research agenda but does not increase certainty beyond the underlying trials.

Taurine may therefore be described as promising and experimental, not recommended as an EHI-prevention supplement. Increased sweat production is useful only when the environment permits evaporation and fluid losses can be managed; in humid conditions, additional sweat may drip without providing proportional cooling. No available trial measured diagnosed EHI, elite competition outcomes or repeated use across a season. The studied 50 $mg \cdot kg^{-1}$ regimen can inform future research and individualized supervised trials, but the present evidence is insufficient for a universal protocol. Certainty is low for acute thermoregulatory and performance effects and very low for EHI prevention.

6.3. Menthol

Menthol activates cold-sensitive TRPM8 receptors and can make the mouth, airway or skin feel cooler without removing a comparable amount of body heat. This distinction is essential. Jeffries and Waldron [28] pooled 13 crossover studies enrolling 135 men; seven used time trials, three used time-to-exhaustion tests, two used fixed-RPE protocols and one ended at a fixed core temperature. Ambient temperature averaged 31°C (SD 5; range 20-35°C), so the evidence set was not restricted to clearly hot conditions. Menthol produced a borderline small overall performance effect (Hedges' g=0.33, 95% CI -0.00 to 0.65; p=0.05; I2=43%). Internal administration was associated with a small effect (g=0.40, 95% CI 0.04-0.76; p=0.03; I2=0%), whereas the external-application subgroup was not significant (g=0.29, 95% CI -0.34 to 0.91; p=0.37; I2=70%).

Thermal sensation was reduced overall (g=-0.54, 95% CI -0.67 to -0.42; p<0.001; I2=67%). External application produced a larger perceptual estimate than internal administration, but heterogeneity for the external subgroup was high (I2=74%) and a greater change in thermal sensation did not consistently translate to improved performance. Twelve of the 13 studies were

single-blinded, leaving outcome assessment vulnerable to recognition of menthol's distinctive sensory effect, and one study had high reporting-bias risk. These findings support a perceptual and possibly performance-related role, not physiological cooling, and their applicability to women remains unknown [28].

A 2026 network meta-analysis of 15 randomized trials compared ingestion, mouth rinsing and topical application. Most pairwise differences were not statistically significant. Ranking probabilities suggested that ingestion might be most favourable for endurance performance and mouth rinsing for mean power, whereas none of the routes produced a significant advantage for core temperature or heart rate. Topical application ranked worst for thermoregulation and could impede heat dissipation when the vehicle covers the skin [29]. These rankings are exploratory and should not be treated as proof that one route is superior.

A topical-specific three-level meta-analysis subsequently included 16 studies, 191 participants (171 men and 20 women) and 34 performance effect sizes. Acute topical menthol produced a small overall performance effect (g=0.27, 95% CI 0.10-0.44), reduced thermal sensation (g=-0.74, 95% CI -0.96 to -0.53) and rating of perceived exertion (g=-0.35, 95% CI -0.63 to -0.07), and slightly improved thermal comfort (g=0.34, 95% CI 0.01-0.67). Core body temperature was unchanged (g=0.02, 95% CI -0.22 to 0.26). The performance effect was not statistically significant in the subgroup exercising in environments of 30°C or hotter (g=0.12; p=0.35), although between-subgroup tests were also non-significant and do not establish a true environmental interaction [30].

These estimates require restraint. Wang et al. rated certainty as low for performance, thermal sensation, perceived exertion and core temperature, and very low for thermal comfort. Only one included study was judged at overall low risk of bias, funnel-plot asymmetry suggested possible small-study effects for performance, thermal sensation and perceived exertion, and the performance prediction interval crossed the null. The practical attraction of menthol is therefore perceptual relief when physical cooling is unavailable, not reliable heat removal. Feeling cooler could theoretically encourage a pace that is not matched by reduced physiological strain, but clinical harm from such perceptual masking has not been demonstrated. Menthol should be rehearsed, used only within an established pacing and hydration plan, and never used to override worsening symptoms or objective safety limits. Confidence is low for a small perceptual or performance benefit and very low for EHI prevention; no direct reduction in heat-illness events has been demonstrated.

6.4. Creatine and other insufficiently supported supplements

Creatine has sometimes been suspected of increasing dehydration or heat-illness risk because it increases intracellular water and can increase body mass. Controlled evidence does not support that concern at recommended doses. A systematic review with meta-analyses found no evidence that creatine impaired hydration status or heat tolerance during exercise [31]. More recent heat-specific syntheses found no significant effect on peak core temperature (Hedges' g=-0.12, 95% CI -0.453 to 0.203) or whole-body sweat rate (g=0.15, 95% CI -0.208 to 0.517) [22]. Creatine can therefore be continued for its established sport-specific indications when individually tolerated, but it should not be prescribed to prevent EHI; evidence for direct clinical protection is absent.

Other supplements should be reported briefly because plausible mechanisms and isolated performance findings have not translated into a reliable heat-safety strategy. For dietary nitrate, Peel et al. [22] found trivial, nonsignificant effects on peak core temperature (g=0.07, 95% CI -0.237 to 0.381) and no clear thermoregulatory advantage. BCAAs likewise showed no meaningful effect on peak core temperature (g=-0.004), while heat-exercise performance trials were inconsistent; a 2025 network meta-analysis found a positive but nonsignificant performance estimate (SMD 0.73) [32]. Probiotics may be relevant to gastrointestinal barrier

integrity, but pooled heat studies showed no effect on peak core temperature or whole-body sweating [22].

Antioxidant and anti-inflammatory supplements form a heterogeneous group rather than a single intervention. Peel et al. [22] found no observable thermoregulatory effect for vitamin C or polyphenols, while apparently favourable findings for agents such as oligonol, catechin, curcumin or vitamin E were agent-specific, often nonsignificant and commonly based on one or a few studies. The review also cautioned that chronic antioxidant supplementation alongside repeated heat exposure may blunt some adaptive responses. These products therefore cannot be recommended collectively for heat protection. Beta-alanine has been discussed among broader ergogenic options for exertional heat exposure [9], but it was not identified as an eligible stand-alone heat intervention in the broad heat-specific syntheses by Li et al. [32] or Peel et al. [22]. Consequently, there is no adequate basis to claim that beta-alanine improves thermoregulation or prevents EHI.

For all agents in this subsection, the decisive limitation is not merely a lack of statistical significance but a mismatch between the outcomes studied and the clinical claim. Changes in endurance tests, core temperature, sweating or gastrointestinal markers are surrogate outcomes; none establishes a reduction in exertional heat exhaustion or EHS. Nitrate, beta-alanine, BCAAs, probiotics and antioxidants should therefore remain in a short evidence-gap paragraph rather than being converted into practical EHI-prevention recommendations.

7. Discussion and differential synthesis of outcomes

7.1. Thermoregulation

The reviewed strategies influence different parts of the heat-balance pathway and should not be grouped under a single concept of 'cooling'. Starting exercise euhydrated and limiting an excessive fluid deficit preserve the circulating volume available for skin blood flow and sweating, but do not actively remove stored heat. Sodium may support retention of an appropriate fluid volume, whereas hyperhydration expands body-water stores before exercise; neither consistently lowers core temperature across protocols [7,13,14]. These are fluid-balance strategies, not evidence that complete replacement of sweat loss is required or that more drinking is invariably safer.

Cold fluids and ice slurry provide genuine internal heat transfer, yet the pooled end-exercise reduction in core temperature is small and sweating may be suppressed. Their net effect depends on whether the environmental evaporative capacity can compensate for that reduction in sweating [17,18]. Taurine operates differently: the available studies suggest increased sweat production and evaporative heat loss, with lower heat storage in a controlled fixed-heat-production model [23,24]. This potential benefit is most plausible in conditions that permit sweat evaporation; additional sweat is less useful in high humidity and increases fluid loss.

Caffeine may increase metabolic heat production and produce a small rise in core temperature, despite increased sweating, whereas creatine, nitrate, BCAAs, probiotics and most antioxidant strategies have not demonstrated a consistent effect on core temperature or sweating [21,22]. Menthol occupies a separate category: route-mixed and topical-specific syntheses show improved thermal sensation, while topical application does not reduce core temperature and route comparisons have not demonstrated a consistent heart-rate benefit [28,29,30]. Therefore, perceived cooling, increased sweating, improved fluid balance and a measured fall in core temperature should remain separate outcomes rather than being treated as interchangeable evidence of reduced thermal strain.

Co-ingestion data reinforce the need to evaluate formulations rather than infer their effect from each ingredient separately. In ten non-heat-acclimated adults (seven men and three women), 5

mg·kg⁻¹ caffeine plus 50 mg·kg⁻¹ taurine increased oxygen consumption, minute ventilation and metabolic heat production relative to placebo, but did not change core temperature, skin temperature, skin blood flow or whole-body sweat rate during cycling at 35°C and 40% relative humidity [26]. Thus, taurine did not produce the sweating response observed in some taurine-only studies, while the greater metabolic demand did not translate into greater measured thermal strain under this protocol.

7.2. Direct EHI outcomes

The largest evidential gap is the absence of trials powered for diagnosed exertional heat exhaustion, EHS or heat-related medical encounters. Most intervention studies enrolled small samples under laboratory supervision and terminated exercise at voluntary exhaustion or a predefined safety threshold. Such designs can establish effects on body mass, plasma volume, core temperature, sweat rate, thermal sensation or performance, but they cannot determine whether an intervention prevents clinical EHI. Accordingly, no hydration, sodium, carbohydrate, internal-cooling or supplement strategy reviewed here should be described as independently reducing EHS incidence.

Epidemiological evidence confirms that clinically recorded EHI is concentrated in endurance events but does not identify the causal effect of a nutritional strategy. In the review by Gamage et al. [3], only a minority of the 62 studies reported specific diagnoses, and dehydration or hyponatraemia was sometimes grouped with other heat-related conditions. Diagnostic terminology, exposure denominators and surveillance methods varied, milder cases were probably underreported, 71% of studies originated in the United States, and eight studies were judged to have low quality or high risk of bias. Westwood et al. [5] reached a complementary conclusion after reviewing 42 primary studies of individual EHI risk factors: susceptibility appeared to reflect an accumulation of interacting factors, while the evidence was dominated by retrospective case-control designs with incomplete reporting, diagnostic uncertainty, uncontrolled confounding and relatively few cases. These reviews are valuable for defining disease burden and research priorities, but they cannot show that greater fluid, sodium or supplement intake prevents EHI.

Competition surveillance illustrates both the value and limitations of direct event data. At the 2016 UCI Road World Championships in Qatar, conducted at a mean direct-sun temperature of 36.9°C and wet-bulb globe temperature of 27.1°C, the Athlete Medical Centre recorded three heat-exhaustion cases among 982 race starters and no diagnosed EHS [33]. The investigators cautioned that the medical centre was not located at the finish and that national-team physicians may have managed additional cases without reporting them. This study confirms that clinically diagnosed events can be captured in elite endurance competition, but it did not test a nutritional intervention and should not be interpreted as an estimate of hydration efficacy.

This limitation does not make the surrogate outcomes irrelevant. Avoiding a substantial pre-exercise fluid deficit, preventing excessive positive fluid balance, preserving opportunities for evaporative heat loss and recognizing worsening symptoms are physiologically and clinically defensible components of risk management [1,2,12]. The strength of the claim must nevertheless match the outcome: reduced thermal strain or improved fluid balance may be compatible with lower risk, but it is not direct evidence of fewer EHI events. Conversely, the small caffeine-associated rise in core temperature and menthol-associated improvement in thermal sensation justify caution, but do not establish that either intervention causes EHI.

Event-level prevention is also inherently multicomponent. Heat acclimation, environmental monitoring, pacing, work-to-rest modification, access to fluids and cooling, symptom recognition and emergency preparedness act together. Even when an observational field programme reports fewer medical encounters after several measures are introduced, its effect cannot be assigned to one beverage, nutrient or supplement without an appropriate comparator.

Direct EHI evidence should therefore be graded separately in the evidence matrix and, for nearly every isolated nutritional intervention, classified as absent or very low certainty.

A directly relevant field signal comes from Li et al. [11], who analysed prospectively collected records from 312 athletes across four hot-humid endurance events and retained 116 propensity-score-matched pairs. A five-component graded cooling and individualized cold-fluid replacement programme was associated with fewer non-serious heat-related medical encounters than usual self-selected practice (10/116 [8.6%] versus 20/116 [17.2%]; conditional odds ratio 0.41, 95% CI 0.17-0.99), a 0.50°C lower post-race core temperature and a 3.08-percentage-point smaller deviation from personal-best race time. No EHS occurred. The result is clinically relevant but low-certainty: allocation was non-randomized, events were few, diagnoses were non-serious and the estimate was imprecise. The five components were a pre-race phase-change cooling vest, pre-race ice slurry, mid-race cold sponges, individualized cold carbohydrate-electrolyte fluid delivered within 10% of the planned volume and immediate post-finish cooling. The study supports the integrated package and its feasibility, not an isolated preventive effect of fluid, ice slurry or any single component.

7.3. Endurance performance

Performance effects depend strongly on the test used. Pre-exercise hyperhydration produced small-to-moderate pooled improvements in time to exhaustion and time-trial outcomes, but not total-work tests; heterogeneity and limited representation of running, women and elite athletes restrict generalization [14]. Internal cooling similarly showed a clearer benefit for time to exhaustion than for self-paced time trials [18]. These differences are important because time-to-exhaustion protocols amplify small physiological or motivational effects and have greater within-participant variability than competition-like self-paced tests.

Carbohydrate remains appropriate fuel for sufficiently prolonged exercise, but heat-specific trials do not show a consistent additional performance benefit, particularly in time trials, and high concentrations can worsen gastrointestinal symptoms [16]. Caffeine is ergogenic in many settings, yet heat-specific findings are inconsistent: the pooled heat-specific estimate at approximately 6 $mg \cdot kg^{-1}$ was +2.1%, but its confidence interval crossed zero, and 5 $mg \cdot kg^{-1}$ did not improve time to exhaustion while increasing thermal strain in a later controlled trial [20,21]. Menthol provides a small average performance effect that appears primarily perceptual. The earlier route-mixed analysis found a clearer effect with internal administration, while the newer topical-specific analysis reported a small low-certainty effect overall but no statistically significant benefit in the subgroup exercising in environments of 30°C or hotter [28,30].

Taurine has improved time to exhaustion in small studies and produced favourable thermoregulatory signals, making it a research priority rather than an established recommendation [23,25]. Creatine, nitrate, BCAAs, probiotics and antioxidants lack consistent heat-specific endurance effects sufficient to guide practice [9,22,32]. Across strategies, laboratory performance gains should be translated cautiously: a result obtained in unacclimatized men cycling to exhaustion cannot be assumed to improve running economy, race time, late-race decision-making or safety during a prolonged outdoor competition.

The null co-ingestion trial further limits generalization. Caffeine plus taurine did not improve time to exhaustion ($p=0.608$) in ten non-heat-acclimated adults despite increasing metabolic and ventilatory demand [26]. This does not refute taurine-only findings because the formulation, timing and comparator differed, but it shows that effects of individual ingredients cannot be assumed to remain additive when combined.

7.4. Population and context modifiers

The applicability of the evidence is narrowed by participant selection. Men comprise the large majority of samples; women, elite athletes, adolescents, masters athletes and individuals with previous heat intolerance are underrepresented. Training and heat-acclimation status are also inconsistently reported. Since acclimation alters plasma volume, sweating, skin blood flow and cardiovascular stability, an intervention effect in unacclimatized participants may be smaller, absent or qualitatively different after adaptation [1,2].

The scale of female underrepresentation is measurable. An audit of 1,407 exercise-thermoregulation studies published from 2010 to 2019 found that women represented only 11.6-17.8% of participants annually; fewer than one third of studies involving women reported menstrual orientation and fewer than one quarter reported both orientation and phase [34]. The menstrual-cycle meta-analysis included only nine studies and 83 naturally menstruating, non-sedentary women who were not using hormonal contraception; inclusion required blood-based verification of cycle phase. Standardized effects indicated higher internal temperature in the luteal phase both before and after exercise, but the corresponding mean absolute differences were only 0.18°C before exercise and 0.05°C after exercise. Pooled whole-body and local sweat rate, mean skin temperature and exercise heart rate did not differ between phases [35]. Interpretation is constrained by PEDro scores of 4-5, non-standardized baseline-temperature protocols and the inability to exclude lower-quality studies from an evidence base this small. A focused fluid-balance review likewise found that cycle-related hormonal effects did not consistently alter sweat rate, exercise heat stress, dehydration or post-exercise fluid retention [36]. In the small crossover trial by Convit et al. [15], sodium hyperhydration increased fluid retention in female cyclists or triathletes across the early-follicular and mid-luteal phases, but no consistent main phase effect was observed. Together, these findings do not justify a universal phase-specific drinking prescription; they support individual monitoring and better reporting of cycle phase and hormonal contraception.

Exercise mode and environmental context further modify the balance of benefit and harm. Cycling dominates the laboratory literature, while added body mass from hyperhydration may be more consequential in running. High humidity limits sweat evaporation and can reduce the value of strategies that primarily increase sweating, whereas air movement and lower humidity may improve their effectiveness [1,13]. Event duration determines whether planned drinking, sodium and carbohydrate delivery become relevant, and access to aid stations determines feasibility. Gastrointestinal tolerance can negate an otherwise plausible protocol, particularly when concentrated carbohydrate, large pre-exercise fluid volumes, glycerol, sodium or several supplements are combined.

Application should remain conditional on the athlete, event and environment. Each strategy should be rehearsed under representative conditions and judged against its intended target: fluid balance, physiological heat strain, perception, performance or clinical safety. Table 1 summarizes these effects and rates direct EHI evidence independently from mechanistic or performance evidence.

Table 1. Differential effects of hydration and nutritional strategies on thermoregulation, endurance performance and direct EHI outcomes.

Strategy	Primary physiological action	Thermoregulation	Endurance performance	Direct EHI outcomes	Evidence-based interpretation
Euhydration and individualized drinking	Supports plasma volume, skin blood flow and sweating; limits	Helps preserve thermoregulatory function when meaningful hypohydration	Context dependent; most relevant during long, intense	No intervention trials demonstrate independent prevention of	Established foundation. Use measured losses and event context; avoid body-mass gain

Strategy	Primary physiological action	Thermoregulation	Endurance performance	Direct EHI outcomes	Evidence-based interpretation
	excessive fluid deficit.	develops; complete sweat-loss replacement is not uniformly required.	exercise with high sweat loss.	EHS; strong safety rationale for avoiding both marked deficit and overdrinking.	during exercise. Confidence: moderate for fluid balance, very low for direct EHI prevention [1,6,7].
Sodium and electrolytes	Supports fluid retention, thirst and beverage palatability when substantial fluid is consumed.	May support plasma sodium and retained volume; does not itself provide cooling.	No consistent independent benefit unless it enables a more appropriate drinking strategy.	Does not prevent EAH when fluid intake exceeds losses; no direct EHI-prevention evidence.	Individualize for long events, high fluid replacement and high sodium losses. Confidence: low-to-moderate for fluid retention, very low for direct EHI [8,12].
Pre-exercise hyperhydration	Expands body-water stores using fluid plus sodium or glycerol.	Some studies report lower heart rate or core temperature, but pooled thermal effects are inconsistent; one small female trial showed greater fluid retention without a consistent menstrual-phase effect.	Small-to-moderate benefit for TTE and TT; no significant benefit for total work.	No trials powered for heat exhaustion or EHS.	Optional for selected long, hot events with limited drinking access; rehearse because of gastrointestinal symptoms and added mass. Confidence: moderate for small performance benefit, very low for EHI [13,14,15].
Carbohydrate	Maintains exogenous fuel availability during sufficiently prolonged exercise.	Generally no reduction in core temperature or improvement in hydration markers.	Mixed heat-specific findings; benefit is not consistently demonstrated, especially in TT protocols.	No direct EHI-prevention evidence.	Retain duration-dependent fuelling principles; do not increase intake solely because it is hot. Confidence: low-to-moderate for performance in the heat, very low for EHI [16,37].
Cold fluids and ice slurry	Absorbs heat as fluid warms and ice melts; may also improve thermal perception.	Small average reduction in end-exercise core temperature; sweating may decrease, so net heat loss depends on environment.	Small benefit for TTE; weaker and statistically uncertain evidence for TT and mean power.	No trials demonstrate fewer clinical EHI events.	Optional adjunct integrated into the total fluid plan. Confidence: moderate for small TTE and thermal effects, very low for EHI [17,18].
Caffeine	Adenosine-receptor antagonism may reduce fatigue perception but can increase metabolic heat production.	Small increase in peak core temperature in pooled analyses; a 5 $mg \cdot kg^{-1}$ trial increased heat production and thermal strain.	Established ergogenicity generally, but inconsistent in heat; the heat-specific pooled estimate crossed the null and a recent 5 $mg \cdot kg^{-1}$ TTE trial found no benefit.	No evidence that caffeine causes or prevents EHI.	Not a cooling strategy. If used, employ the lowest effective rehearsed dose and avoid escalation in heat. Confidence: low-to-moderate for a small adverse thermal effect, very low for EHI [20,21,22].
Taurine	May increase sweating and evaporative heat loss.	Promising reductions in heat storage or late-exercise core temperature; evidence	Improved TTE in some small taurine trials, but caffeine-taurine co-	No diagnosed EHI outcomes.	Promising but experimental; do not extrapolate taurine-only effects to

Strategy	Primary physiological action	Thermoregulation	Endurance performance	Direct EHI outcomes	Evidence-based interpretation
		comes from few small trials. Caffeine-taurine co-ingestion did not alter core temperature or sweating.	ingestion did not improve TTE.		combined products. Confidence: low for thermoregulation and performance, very low for EHI [23,24,26].
Menthol	TRPM8-mediated perceptual cooling without equivalent heat removal.	Improves thermal sensation, but topical application does not reduce core temperature and route comparisons show no consistent heart-rate benefit.	The 2019 all-male analysis found a borderline small overall effect; internal administration was significant but external application was not. A later topical-specific analysis found a small low-certainty effect and no significant benefit at 30°C or hotter.	No direct prevention evidence; perceptual masking is a safety concern rather than a demonstrated clinical harm.	Use only with objective pacing and symptom limits. Confidence: low for perception and performance, very low for EHI [28,29,30].
Creatine	Increases intracellular water and supports phosphagen availability.	No significant adverse or beneficial pooled effect on peak core temperature or sweating.	Heat-specific endurance evidence is inconsistent; established uses relate mainly to other performance demands.	Controlled trials have not shown impaired heat tolerance at recommended doses; no direct EHI-prevention evidence.	May be continued for established indications when tolerated, but not prescribed for heat protection. Confidence: moderate for absence of major thermal harm, very low for EHI [22,31].
Nitrate, beta-alanine, BCAAs, probiotics and antioxidants	Heterogeneous proposed actions involving nitric oxide, buffering, central fatigue, gut integrity or redox balance.	No consistent clinically meaningful effect; beta-alanine lacks adequate stand-alone heat-specific evidence.	Inconsistent, nonsignificant or insufficient heat-specific results.	No direct EHI outcomes.	Do not recommend for thermoregulation or EHI prevention. Confidence: low or very low, depending on agent [9,22,32].
Multicomponent event programme	Combines a pre-race phase-change vest and ice slurry, mid-race cold sponges and individualized cold carbohydrate-electrolyte fluid, and immediate post-finish cooling.	One matched field cohort found 0.50°C lower post-race core temperature.	One field cohort found a 3.08-percentage-point smaller deviation from personal-best time.	Medical encounters were 10/116 versus 20/116 (OR 0.41, 95% CI 0.17-0.99); no EHS occurred.	Supportive real-world evidence for the package, not its individual components. Confidence: low because the study was observational and events were few [11].

Source: Authors' own synthesis based on the cited literature.

8. Practical recommendations

8.1. Before exercise

The primary objective before endurance exercise in the heat is to begin without a meaningful fluid deficit and with a familiar fuelling plan. This does not require forced water loading. Athletes should use training sessions in comparable conditions to estimate changes in body mass, usual drinking opportunities, gastrointestinal tolerance and the practical range of fluid intake that prevents both an excessive deficit and positive fluid balance. The estimate should guide a range rather than a rigid target because pace, weather, clothing and access to aid stations can change on the day [1,6,7].

Female athletes should not be given a universally higher fluid or sodium target solely on the basis of menstrual-cycle phase. In the available meta-analysis, mean internal temperature was 0.18°C higher before exercise and 0.05°C higher after exercise in the luteal phase, while pooled sweat rate, exercise heart rate and mean skin temperature did not differ. The analysis included only nine studies and 83 naturally menstruating, non-sedentary women not using hormonal contraception, did not assess diagnosed EHI and had important methodological limitations [35]. Current evidence also does not demonstrate consistent cycle-related changes in exercise dehydration or post-exercise fluid retention [36]. A 12-participant sodium-hyperhydration trial found no consistent main menstrual-phase effect, despite improved fluid retention overall [15]. Individual symptom patterns, measured sweat losses, hormonal-contraceptive use and prior responses in comparable conditions are therefore more defensible guides than calendar-based prescriptions.

Pre-exercise hyperhydration is an optional strategy, not a prerequisite for safe participation. It is most defensible before prolonged exercise in which high sweat losses are expected and access to fluid is limited. Sodium- or glycerol-based protocols should be rehearsed because large fluid volumes, gastrointestinal symptoms and added body mass may offset the small performance benefit, particularly during running. The protocols reported in studies, including the sodium-chloride protocol studied in 12 female cyclists or triathletes, should not be converted into universal prescriptions, and hyperhydration should not be used to justify faster pacing or to compensate for inadequate heat acclimation [13,14,15].

Carbohydrate availability should follow the expected duration and intensity of exercise. Current evidence does not support increasing carbohydrate intake solely because conditions are hot; concentration, form and timing should be adjusted to tolerance [16]. Pre-exercise cold-fluid or ice-slurry ingestion can be considered when logistically feasible, but the volume must be included in the total fluid plan. Commonly studied doses are research protocols rather than minimum requirements, and smaller, tolerable amounts may be preferable to a large dose that causes fullness, nausea or headache [18].

No supplement should be introduced for the first time on competition day. Caffeine users should favour the lowest previously effective dose and avoid dose escalation in the heat because performance benefit is inconsistent and core temperature may rise slightly [20,21]. Taurine remains experimental despite promising thermoregulatory findings [23,24], and menthol should be understood as perceptual cooling rather than heat removal [28,29,30]. Creatine may be continued for an established indication when well tolerated, but neither creatine nor nitrate, beta-alanine, BCAAs, probiotics or antioxidants should be started specifically to prevent EHI [22,31].

8.2. During exercise

Drinking during exercise should be individualized to event duration, intensity, environment and access. Thirst-guided drinking is reasonable for many shorter or lower-intensity sessions and provides protection against overconsumption. A more deliberate plan becomes useful during

prolonged, intense exercise in the heat, particularly for athletes with high measured sweat losses or when fluid and carbohydrate delivery must be coordinated. Even then, the plan should remain adjustable rather than functioning as a compulsory hourly volume [7].

Avoiding overdrinking is a firm safety boundary. Fluid intake should not deliberately produce body-mass gain during exercise, and sodium does not make excessive drinking safe. Sodium-containing drinks or foods may assist retention, palatability and maintenance of plasma sodium when substantial fluid replacement is appropriate, but gram-for-gram replacement of all sweat sodium is not routinely required. An athlete who slows unexpectedly, develops gastrointestinal symptoms or encounters cooler conditions should reduce intake rather than continue a pre-set volume unchanged [8,12].

Carbohydrate should be delivered according to the energetic demands of the event and the athlete's tested gastrointestinal capacity. Highly concentrated drinks or aggressive intake targets may increase nausea and fullness in the heat [16]. Cold fluids or ice slurry may provide a small perceptual or thermal benefit and can be useful at aid stations, but they count toward total fluid intake and should not displace necessary carbohydrate or sodium without a planned alternative [17,18]. Menthol may improve thermal sensation, yet should never be used as evidence that physiological strain has fallen [28,29,30].

Pacing and symptom monitoring remain essential because no drink or supplement neutralizes uncompensable heat stress. Athletes should respond to unexpected weakness, dizziness, vomiting, confusion, altered behaviour, loss of coordination, collapse or progressive deterioration by stopping exercise and seeking assessment. Sweating status alone should not be used to exclude EHS. Subjective cooling from menthol or ice must not be used to override symptoms. These recommendations are safety boundaries derived from the broader EHI and heat-event literature, not proof that a particular nutritional product prevents EHS [1,2].

8.3. Integrated event-level strategies and safety boundaries

Nutritional strategies should sit within an event-level heat plan that includes heat acclimation, environmental monitoring, realistic pacing, work-to-rest or competition modifications where applicable, shaded or cooled recovery areas, access to fluids, trained medical personnel and a rehearsed emergency pathway. Because these measures interact, the effectiveness of a multicomponent programme cannot be assigned to one beverage or supplement. The most credible approach is to combine established organizational controls with a small number of individualized nutritional measures rather than layering multiple untested products [1,2].

Real-world evidence now supports testing such packages prospectively. In Li et al. [11], the organizer-delivered programme was completed with at least four of five components by 94.8% of matched participants, and median delivery time at the mid-race station was 44 s. Its association with fewer medical encounters remained directionally similar when heat-related withdrawals were included. These implementation data support feasibility, but the observational allocation, small number of medical events and inseparable intervention components mean that the programme should be presented as promising low-certainty evidence rather than a proven EHS-prevention protocol.

Preventive cooling must also be separated from treatment. Cold drinks, ice slurry, menthol and pre-cooling may be used before or during exercise by an otherwise well athlete, but they are not treatment for suspected EHS. Once EHS is suspected, exercise must stop and emergency assessment and rapid whole-body cooling take priority; continued oral intake can be inappropriate when consciousness or airway protection is impaired. Detailed recognition and treatment protocols fall outside this review and should follow current emergency guidance [2,10].

EAH must remain in the differential diagnosis of a symptomatic endurance athlete. Headache, nausea, weakness, confusion or collapse may occur in both EAH and heat illness, and automatic

administration of additional hypotonic fluid can worsen EAH. Body-mass gain, bloating and a history of high fluid intake increase suspicion, but definitive assessment may require plasma sodium measurement. The preventive message is simple: avoid forced drinking, do not interpret sodium intake as permission to exceed losses, and ensure event staff recognize that dehydration is not the only fluid-related emergency [12].

A practical hierarchy follows. Establish acclimation, pacing and event safeguards first. Begin euhydrated and use an individualized drinking and fuelling plan; add sodium or internal cooling when the event supports them; reserve hyperhydration for selected, rehearsed situations; and treat taurine and menthol as experimental or perceptual aids. Table 2 identifies the intended context, expected benefit, safety boundary and confidence for each recommendation.

Table 2. Practical application, safety boundaries and certainty of evidence.

Timing	Strategy	Most applicable context	Practical application	Expected benefit	Safety boundary and direct EHI evidence	Confidence
Before	**Start euhydrated**	All endurance exercise in the heat; especially long or high-sweat-loss events.	Use representative training to estimate losses and arrive without a meaningful deficit; do not force excess fluid.	Supports fluid balance, skin blood flow and sweating.	Does not guarantee prevention of EHS. Avoid pre-start body-mass gain from indiscriminate loading.	Moderate for fluid balance; very low for direct EHI prevention [1,6,7].
Before / during	**Female-specific monitoring**	Female athletes, especially when an individual reports cycle- or contraception-related changes in heat tolerance.	Track symptoms, sweat loss and response in representative sessions; record cycle phase and hormonal contraception where relevant.	May identify individual patterns; pooled absolute temperature differences were small, sweat rate did not differ by phase, and one small sodium-hyperhydration trial found no consistent main phase effect.	Do not prescribe extra fluid or sodium solely by menstrual phase; direct EHI-prevention evidence is absent.	Low for phase-specific modification because the evidence remains sparse; very low for direct EHI [15,35,36].
Before	**Selective hyperhydration**	Long hot events with restricted drinking access and demonstrated high losses.	Use only a previously tolerated sodium- or glycerol-based protocol; treat published doses as study protocols, not universal prescriptions.	Possible small improvement in TTE or TT; inconsistent thermal effect; sodium increased fluid retention in one small female trial.	GI symptoms and added mass may offset benefit. No direct EHI-event evidence.	Moderate for small performance benefit; very low for EHI [13,14,15].
Before / during	**Carbohydrate**	Exercise long enough to require exogenous fuel.	Follow duration-dependent targets already tolerated by the athlete; adjust concentration, form and timing rather than increasing intake because of heat alone.	Maintains fuel availability; heat-specific performance benefit is inconsistent.	High concentrations may worsen nausea or fullness. No cooling or direct EHI-prevention evidence.	Low-to-moderate for heat-specific performance; very low for EHI [16,37].
Before / during	**Cold fluids or ice slurry**	Hot events where cold products are	Integrate a rehearsed volume into the total drinking plan;	Small reduction in thermal strain or improved	May suppress sweating; benefit depends on evaporation.	Moderate for small surrogate/TTE effects; very low for EHI [17,18].

Timing	Strategy	Most applicable context	Practical application	Expected benefit	Safety boundary and direct EHI evidence	Confidence
		available and tolerated.	combine with fuel and sodium needs where appropriate.	TTE/perception in some settings.	Count all volume to avoid overdrinking. No direct EHI-event evidence.	
During	**Thirst-guided drinking**	Shorter, lower-intensity or slower events with frequent fluid access.	Drink in response to thirst while monitoring symptoms and event conditions.	Limits unnecessary intake and usually prevents severe overdrinking.	May under-replace rapid losses in selected long, intense events. No independent EHI-prevention trial evidence.	Moderate for fluid-balance safety; very low for direct EHI [7,12].
During	**Planned individualized drinking**	Prolonged intense exercise, high measured sweat rate, coordinated carbohydrate delivery or limited aid access.	Use a rehearsed intake range based on representative conditions; adjust for pace, weather, GI symptoms and access.	Can limit a substantial fluid deficit and coordinate fuel delivery.	Do not force the planned volume or allow body-mass gain. No proof that full sweat replacement prevents EHS.	Moderate for fluid balance; very low for direct EHI [1,7].
During	**Sodium and electrolytes**	Long events with substantial fluid intake or high sodium loss.	Use food or drinks to complement the fluid plan; individualize concentration and delivery method.	May aid retention, palatability and maintenance of plasma sodium.	Cannot neutralize overdrinking or guarantee prevention of EAH/EHI.	Low-to-moderate for retention; very low for direct EHI [8,12].
Before	**Caffeine**	Experienced users seeking an ergogenic effect after successful heat-specific rehearsal.	Use the lowest previously effective dose; include all sources and avoid escalation in heat.	Performance benefit is possible but inconsistent in hot conditions.	May slightly increase core temperature and thermal strain. No causal EHI evidence.	Low-to-moderate for small thermal effect; variable for performance; very low for EHI [20,21].
Before / during	**Menthol**	Selected athletes seeking perceptual relief when physical cooling is limited.	Use a previously rehearsed product and route within fixed pacing and symptom limits; do not treat internal or topical menthol as physical cooling.	Improves thermal sensation; small possible performance effect, but topical evidence in hot environments is not significant.	Does not reduce core temperature reliably and may mask strain. No direct EHI benefit.	Low for perception and performance; very low for EHI [28,29,30].
Before	**Taurine**	Research or carefully supervised individualized trial; not routine competition practice.	The studied 50 $mg \cdot kg^{-1}$ protocol may guide research, but evidence is insufficient for a universal recommendation.	Promising sweating and thermal responses; small-study TTE benefit.	More sweating increases fluid loss and may not cool effectively in humidity. No clinical EHI outcomes.	Low for thermoregulation and performance; very low for EHI [23,24,26].
Event level	**Heat plan and emergency pathway**	All organized hot-weather endurance events.	Combine acclimation, environmental monitoring, pacing, shade or cooling,	Supports prevention and response; one cohort reported fewer non-serious heat-related	Preventive aids are not EHS treatment; no EHS occurred in either field study, and	Moderate-to-high for established organizational safeguards; low for the specific field package and

Timing	Strategy	Most applicable context	Practical application	Expected benefit	Safety boundary and direct EHI evidence	Confidence
			trained staff and an emergency plan.	medical encounters, while separate elite-event surveillance documented three heat-exhaustion cases among 982 starters.	effects cannot be attributed to one component.	direct EHI effect [2,11,33].

Source: Authors' own synthesis based on the cited literature.

9. Limitations of the evidence and research priorities

This review also has methodological limitations. PubMed/MEDLINE was the primary database, supplemented by reference-list checking and focused searches rather than a formal multi-database systematic search. Study selection and confidence judgments were purposive and narrative; records were not screened independently in duplicate, no protocol was registered, and no new risk-of-bias assessment or meta-analysis was performed. Relevant studies may therefore have been missed, and the confidence categories should not be interpreted as formal GRADE ratings. The structured outcome framework and verification of numerical claims against the available publications reduce, but do not eliminate, these limitations.

The principal limitation of this evidence base is the distance between the outcomes commonly measured and the clinical outcome implied by EHI prevention. Most studies quantified core temperature, sweating, heart rate, body-mass change, thermal perception or laboratory performance. These outcomes clarify mechanisms and physiological strain, but none is equivalent to diagnosed heat exhaustion, EHS or a heat-related medical encounter. Trials were generally too small and too closely supervised to estimate rare clinical events, and exercise was commonly terminated at voluntary exhaustion or a predefined safety threshold. Consequently, confidence in direct EHI prevention remains very low for every isolated hydration, nutritional or supplement strategy reviewed.

The participant samples also limit generalizability. Men accounted for most participants in the hyperhydration, internal-cooling and supplement literature, while women were absent or represented by small subgroups. Across 1,407 exercise-thermoregulation studies published from 2010 to 2019, women accounted for only 11.6-17.8% of participants annually, and menstrual-cycle characteristics were usually unreported [34]. The available menstrual-cycle meta-analysis included only nine studies and 83 naturally menstruating, non-sedentary women who were not using hormonal contraception. Included studies had PEDro scores of 4-5, initial internal-temperature assessment was not standardized, and outcomes did not include diagnosed EHI [35]. A recent sodium-hyperhydration study added only 12 female cyclists or triathletes and was not powered for clinical events or definitive phase-specific effects [15]. The topical-menthol meta-analysis likewise included 171 men but only 20 women and no female-only study [30]. Elite athletes, adolescents, masters athletes, individuals with previous EHI and athletes with clinically relevant heat intolerance were also rarely studied. Future trials should be designed and powered to examine sex-specific responses, include menstrual-cycle and hormonal-contraceptive information where relevant, and report training and acclimation status rather than treating heterogeneous athletes as one population.

External validity is further restricted by the dominance of laboratory cycling. Cycling facilitates physiological measurement but does not reproduce the mechanical cost of carrying added body

mass during running, the variable airflow and solar load of outdoor competition, or the tactical decisions that influence self-selected pace. Time-to-exhaustion protocols were common and often produced larger effects than time trials; they should not be treated as interchangeable with race performance. Future work should prioritize pre-registered self-paced trials, running and triathlon protocols, elite competition simulations and pragmatic field studies conducted across realistic combinations of temperature, humidity, radiant heat, air movement and clothing.

Intervention heterogeneity creates an additional interpretive problem. Fluid volumes, beverage temperatures, carbohydrate concentrations, sodium and glycerol doses, supplement timing, exercise intensity and outcome definitions varied substantially. Several strategies were delivered as combinations, making it difficult to isolate the active component. Gastrointestinal symptoms and other adverse effects were inconsistently assessed, even though poor tolerance may determine whether a protocol is usable. Core-temperature measurement sites and sweat-rate methods also differed. Future studies should use standardized reporting of environmental conditions, heat-production requirements, hydration status, measurement methods, adherence and adverse events, and should publish individual responses in addition to group means.

The supplement evidence requires particular restraint. Taurine showed favourable thermoregulatory signals, but pooled estimates depended on few small studies. Menthol primarily altered perception; its topical evidence was graded low or very low and showed potential small-study effects. Caffeine produced inconsistent performance effects with a small adverse thermal signal, and the remaining agents lacked consistent heat-specific benefits. Replication by independent groups is needed before dose-specific recommendations are justified. Trials should compare candidate supplements against established measures such as acclimation, pacing and internal cooling, rather than only against placebo, and should determine whether any incremental benefit remains after these controls are optimized.

The highest research priority remains prospective event-level evidence. Li et al. [11] provide an important field signal: in 116 matched pairs, a multicomponent graded cooling and individualized fluid-replacement programme was associated with fewer heat-related medical encounters (10 versus 20), but no EHS occurred and the observational design could not isolate individual components. Large registries and cluster-randomized or stepped-wedge evaluations should relate predefined hydration and cooling policies to standardized diagnoses of EHI, EAH, medical encounters, withdrawal and performance while accounting for weather, pace, sex, acclimation and previous illness. Until replicated, the Li et al. finding should remain low-certainty supportive evidence for a package rather than proof that hydration or cooling independently prevents EHI.

Existing EHI surveillance also has important methodological limitations. The systematic review by Gamage et al. [3] found substantial heterogeneity in diagnostic terminology and case definitions, probable underreporting of milder conditions and marked geographic concentration in the United States. Westwood et al. [5] likewise identified incomplete reporting, limited diagnostic differentiation, uncontrolled confounding and few cases in much of the risk-factor literature. Studies variously reported cases per athletic-exposure, per participant, as a proportion of medical encounters or as hospitalisations and fatalities, preventing direct comparison of many estimates. Future event registries should use standardized diagnostic criteria and denominators, distinguish EHS, heat exhaustion, syncope, EAH and dehydration, and document the preventive policies operating at each event.

10. Conclusions

Hydration and nutritional strategies have differential effects on fluid balance, thermoregulation, perception and endurance performance, and these outcomes should not be used

interchangeably. The most defensible foundation is to begin exercise without a meaningful fluid deficit, select thirst-guided or more deliberate drinking according to event demands, and avoid intake that produces positive fluid balance. Sodium can support an appropriate fluid plan but cannot make overdrinking safe, while carbohydrate should remain a duration- and tolerance-dependent fuelling strategy rather than a heat-specific cooling intervention.

Pre-exercise hyperhydration and internal cooling may provide small performance or thermoregulatory benefits in selected prolonged events, but their use should be rehearsed and adjusted for gastrointestinal tolerance, added mass, fluid availability and environmental evaporative capacity. Caffeine is not a cooling strategy and may slightly increase thermal strain. Menthol improves thermal sensation without reliable physiological cooling. Taurine is promising, particularly for sweating and heat dissipation, but remains experimental. Creatine does not appear to impair heat tolerance at recommended doses, whereas nitrate, beta-alanine, BCAAs, probiotics and antioxidant supplements currently lack sufficient evidence to support heat-specific recommendations.

No isolated nutritional intervention reviewed here has been shown to prevent clinical EHS. Most evidence concerns surrogate physiological or performance outcomes, and direct EHI-event data are scarce. Nutritional measures should therefore be embedded within a broader heat-risk plan incorporating acclimation, appropriate pacing, environmental monitoring, access to cooling and fluid, symptom recognition and an emergency response pathway. Preventive drinks, ice slurry or perceptual cooling aids do not replace immediate withdrawal, clinical assessment and rapid cooling when EHS is suspected.

For athletes and practitioners, the practical implication is to use a small number of individualized and rehearsed strategies with clearly defined objectives and safety boundaries. For researchers, the priority is adequately powered field evidence that separately reports thermoregulation, performance, adverse events and diagnosed EHI. This outcome-specific approach provides a more credible basis for decision-making than assuming that improved hydration, a lower thermal sensation or a laboratory performance gain necessarily translates into prevention of exertional heat illness.

Disclosure

Supplementary Materials

Not applicable.

Author Contributions

Conceptualization, AG and JD; methodology, AG and LJ; investigation, AG, JD, KL, LJ, KD, KG, NW, MS and SK; resources, JD, KL, KD, KG, NW, MS and KS; data curation, AG, JD, KL, LJ and KD; writing – original draft preparation, AG, JD and KL; writing – review and editing, all authors; visualization, AG, KG and NW; validation, KL, MS and SK; project administration, AG. All authors have read and agreed to the submitted version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable. This narrative review did not involve new research with human participants or animals.

Informed Consent Statement
Not applicable.

Data Availability Statement
No new datasets were generated or analysed. All data discussed in this review are available in the cited publications.

Acknowledgements
Not applicable.

Conflicts of Interest
The authors declare no conflict of interest.

Declaration of the Use of Generative AI and AI-Assisted Technologies in the Writing Process
During the preparation of this work, the authors used ChatGPT (OpenAI) to support English-language drafting and refinement, improve clarity and readability, organize and format the text, verify bibliographic style, and structure evidence tables based on information from the cited publications. The tool was not treated as a source of scientific evidence or as a substitute for author judgement. The authors critically reviewed and edited all AI-assisted content, verified study details, numerical results, and references against the cited publications, and accept full responsibility for the content and conclusions of the manuscript.

References

[1] Périard JD, Eijsvogels TMH, Daanen HAM. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev. 2021;101(4):1873-1979. https://doi.org/10.1152/physrev.00038.2020

[2] Racinais S, Hosokawa Y, Akama T, Bermon S, Bigard X, Casa DJ, Grundstein A, Jay O, Massey A, Migliorini S, Mountjoy M, Nikolic N, Pitsiladis YP, Schobersberger W, Steinacker JM, Yamasawa F, Zideman DA, Engebretsen L, Budgett R. IOC consensus statement on recommendations and regulations for sport events in the heat. Br J Sports Med. 2023;57(1):8-25. https://doi.org/10.1136/bjsports-2022-105942

[3] Gamage PJ, Fortington LV, Finch CF. Epidemiology of exertional heat illnesses in organised sports: a systematic review. J Sci Med Sport. 2020;23(8):701-709. https://doi.org/10.1016/j.jsams.2020.02.008

[4] Lee JKW, Tan B, Ogden HB, Chapman S, Sawka MN. Exertional heat stroke: nutritional considerations. Exp Physiol. 2022;107(10):1122-1135. https://doi.org/10.1113/EP090149

[5] Westwood CS, Fallowfield JL, Delves SK, Nunns M, Ogden HB, Layden JD. Individual risk factors associated with exertional heat illness: a systematic review. Exp Physiol. 2021;106(1):191-199. https://doi.org/10.1113/EP088458

[6] McCubbin AJ, Allanson BA, Caldwell Odgers JN, Cort MM, Costa RJS, Cox GR, Crawshay ST, Desbrow B, Freney EG, Gaskell SK, Hughes D, Irwin C, Jay O, Lalor BJ, Ross MLR, Shaw G, Périard JD, Burke LM. Sports Dietitians Australia position statement: nutrition for exercise in hot environments. Int J Sport Nutr Exerc Metab. 2020;30(1):83-98. https://doi.org/10.1123/ijsnem.2019-0300

[7] Kenefick RW. Drinking strategies: planned drinking versus drinking to thirst. Sports Med. 2018;48(Suppl 1):31-37. https://doi.org/10.1007/s40279-017-0844-6

[8] McCubbin AJ. Sodium intake for athletes before, during and after exercise: review and recommendations. Performance Nutrition. 2025;1:11. https://doi.org/10.1186/s44410-025-00011-9
[9] Dunn RA, Tinsley GM, Palmer TB, Benjamin CL, Sekiguchi Y. The efficacy of nutritional strategies and ergogenic aids on acute responses and chronic adaptations to exertional-heat exposure: a narrative review. Nutrients. 2024;16(22):3792. https://doi.org/10.3390/nu16223792
[10] Mazelanik Ł, Kazimierczuk K, Pawlak J, Czernecka K, Smędowski I, Mordko N, Góras M, Dranikowski K, Markiewicz A, Oknińska-Ziarek A. Exertional heat stroke-recognition and cooling protocols: a narrative review. Quality in Sport. 2026;74:75372. https://doi.org/10.12775/QS.2026.74.75372
[11] Li H, Cao X, Feng S. Mitigating exertional heat illness risk and preserving performance in mass-participation endurance events: a real-world analysis of a graded cooling and fluid replacement strategy. J Sci Med Sport. 2026. Advance online publication. https://doi.org/10.1016/j.jsams.2026.09.007
[12] Bennett BL, Hew-Butler T, Rosner MH, Myers T, Lipman GS. Wilderness Medical Society clinical practice guidelines for the management of exercise-associated hyponatremia: 2019 update. Wilderness Environ Med. 2020;31(1):50-62. https://doi.org/10.1016/j.wem.2019.11.003
[13] Jardine WT, Aisbett B, Kelly MK, Burke LM, Ross ML, Condo D, Périard JD, Carr AJ. The effect of pre-exercise hyperhydration on exercise performance, physiological outcomes and gastrointestinal symptoms: a systematic review. Sports Med. 2023;53(11):2111-2134. https://doi.org/10.1007/s40279-023-01885-2
[14] McCubbin AJ, Irwin C. The effect of pre-exercise oral hyperhydration on endurance exercise performance, heart rate, and thermoregulation: a meta-analytical review. Appl Physiol Nutr Metab. 2024;49(5):569-583. https://doi.org/10.1139/apnm-2023-0384
[15] Convit L, Orellana L, Périard JD, Carr AJ, Warmington S, Mruthunjaya AKV, Torriero AAJ, Snipe RMJ. Hydration responses to pre-exercise sodium hyperhydration at rest and during cycling in the heat and across menstrual cycle phases. Nutrients. 2025;17(23):3672. https://doi.org/10.3390/nu17233672
[16] Salame A, Brown D, Oueijan K, McCullough D. Carbohydrate supplementation for endurance exercise in the heat: a systematic review with practical recommendations. J Int Soc Sports Nutr. 2026;23(1):2669307. https://doi.org/10.1080/15502783.2026.2669307
[17] Jay O, Morris NB. Does cold water or ice slurry ingestion during exercise elicit a net body cooling effect in the heat? Sports Med. 2018;48(Suppl 1):17-29. https://doi.org/10.1007/s40279-017-0842-8
[18] Heydenreich J, Koehler K, Braun H, Grosshauser M, Heseker H, Koenig D, Lampen A, Mosler S, Niess A, Schek A, Carlsohn A. Effects of internal cooling on physical performance, physiological and perceptional parameters when exercising in the heat: a systematic review with meta-analyses. Front Physiol. 2023;14:1125969. https://doi.org/10.3389/fphys.2023.1125969
[19] Guest NS, VanDusseldorp TA, Nelson MT, Grgic J, Schoenfeld BJ, Jenkins NDM, Arent SM, Antonio J, Stout JR, Trexler ET, Smith-Ryan AE, Goldstein ER, Kalman DS, Campbell BI. International Society of Sports Nutrition position stand: caffeine and exercise performance. J Int Soc Sports Nutr. 2021;18(1):1. https://doi.org/10.1186/s12970-020-00383-4
[20] Naulleau C, Jeker D, Pancrate T, Claveau P, Deshayes TA, Burke LM, Goulet EDB. Effect of pre-exercise caffeine intake on endurance performance and core temperature regulation

during exercise in the heat: a systematic review with meta-analysis. Sports Med. 2022;52(10):2431-2445. https://doi.org/10.1007/s40279-022-01692-1
[21] John K, Kathuria S, Peel J, Page J, Aitkenhead R, Felstead A, Heffernan SM, Jeffries O, Tallent J, Waldron M. Caffeine ingestion compromises thermoregulation and does not improve cycling time to exhaustion in the heat amongst males. Eur J Appl Physiol. 2024;124(8):2489-2502. https://doi.org/10.1007/s00421-024-05460-z
[22] Peel JS, McNarry MA, Heffernan SM, Nevola VR, Kilduff LP, Waldron M. The effect of dietary supplements on core temperature and sweating responses in hot environmental conditions: a meta-analysis and meta-regression. Am J Physiol Regul Integr Comp Physiol. 2025;328(4):R515-R555. https://doi.org/10.1152/ajpregu.00186.2024
[23] Page LK, Jeffries O, Waldron M. Acute taurine supplementation enhances thermoregulation and endurance cycling performance in the heat. Eur J Sport Sci. 2019;19(8):1101-1109. https://doi.org/10.1080/17461391.2019.1578417
[24] Peel JS, McNarry MA, Heffernan SM, Nevola VR, Kilduff LP, Coates K, Dudley E, Waldron M. The effect of 8-day oral taurine supplementation on thermoregulation during low-intensity exercise at fixed heat production in hot conditions of incremental humidity. Eur J Appl Physiol. 2024;124(9):2561-2576. https://doi.org/10.1007/s00421-024-05478-3
[25] Yu P, Fan Y, Wu H. Effects of caffeine-taurine co-ingestion on endurance cycling performance in high temperature and humidity environments. Sports Health. 2024;16(5):711-721. https://doi.org/10.1177/19417381241231627
[26] Aggett J, Page J, Peel J, John K, Matta G, Tallent J, Heffernan S, Jeffries O, Waldron M. Acute effects of caffeine and taurine co-ingestion on time to exhaustion and thermoregulatory responses to cycling in the heat. Eur J Sport Sci. 2025;25:e70044. https://doi.org/10.1002/ejsc.70044
[27] Naddafha S, Stout JR, Evans C. Taurine supplementation and human heat tolerance: mechanisms, evidence, and integration with heat acclimation, cooling, and hydration. Nutrients. 2026;18(4):592. https://doi.org/10.3390/nu18040592
[28] Jeffries O, Waldron M. The effects of menthol on exercise performance and thermal sensation: a meta-analysis. J Sci Med Sport. 2019;22(6):707-715. https://doi.org/10.1016/j.jsams.2018.12.002
[29] Zhu Y, Zhao J, Yao J, Wang H, Yuan X. Effects of different menthol administration routes on endurance performance and physiological responses in the heat: a network meta-analysis. Front Nutr. 2026;13:1833420. https://doi.org/10.3389/fnut.2026.1833420
[30] Wang Y, Fan X, Li H, Zhang X, Yin M, Xu K, Zhong Y, Zhang Y, Cui J, Song T, Liu P, Deng H. Acute topical menthol application and exercise performance: a systematic review and meta-analysis of perceptual and physiological responses. J Therm Biol. 2026;140:104529. https://doi.org/10.1016/j.jtherbio.2026.104529
[31] Lopez RM, Casa DJ, McDermott BP, Ganio MS, Armstrong LE, Maresh CM. Does creatine supplementation hinder exercise heat tolerance or hydration status? A systematic review with meta-analyses. J Athl Train. 2009;44(2):215-223. https://doi.org/10.4085/1062-6050-44.2.215
[32] Li J, Liu S, Wang S, Wu Y, Yang L, Luo Q, Li Z, Yang S, Zhao K, Liu C. Effects of nutritional supplements on endurance performance and subjective perception in athletes exercising in the heat: a systematic review and network meta-analysis. Nutrients. 2025;17(13):2141. https://doi.org/10.3390/nu17132141
[33] Racinais S, Nichols D, Travers G, Moussay S, Belfekih T, Farooq A, Schumacher YO, Périard JD. Health status, heat preparation strategies and medical events among elite cyclists who competed in the heat at the 2016 UCI Road World Cycling Championships in

Qatar. Br J Sports Med. 2020;54(16):1003-1007. https://doi.org/10.1136/bjsports-2019-100781
[34] Hutchins KP, Borg DN, Bach AJE, Bon JJ, Minett GM, Stewart IB. Female (under)representation in exercise thermoregulation research. Sports Med Open. 2021;7(1):43. https://doi.org/10.1186/s40798-021-00334-6
[35] Giersch GEW, Morrissey MC, Katch RK, Colburn AT, Sims ST, Stachenfeld NS, Casa DJ. Menstrual cycle and thermoregulation during exercise in the heat: a systematic review and meta-analysis. J Sci Med Sport. 2020;23(12):1134-1140. https://doi.org/10.1016/j.jsams.2020.05.014
[36] Rodriguez-Giustiniani P, Rodriguez-Sanchez N, Galloway SDR. Fluid and electrolyte balance considerations for female athletes. Eur J Sport Sci. 2022;22(5):697-708. https://doi.org/10.1080/17461391.2021.1939428
[37] Nassif C, Cannon J, Marino FE. Skeletal muscle twitch relaxation kinetics following heat stress endurance: carbohydrate versus placebo. Eur J Appl Physiol. 2026;126(10):5643-5653. https://doi.org/10.1007/s00421-026-06368-6