

SYSTEMATIC REVIEW

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Effects of Intermittent Hypoxia Protocols on Physical Performance in Trained and Untrained Individuals: An Umbrella Review of Systematic Reviews and Meta-Analyses

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Abstract

Background Intermittent hypoxia (IH) has emerged as a promising strategy to enhance physical performance by eliciting adaptive responses across cardiovascular, respiratory, and muscular systems. Various IH protocols have been applied in both trained and untrained individuals to improve aerobic capacity, strength, and repeated sprint ability. However, the growing number of systematic reviews and meta-analyses (SRs/MAs) has led to heterogeneous conclusions due to variability in populations, protocols, and outcome measures. This umbrella review aimed to synthesize and critically appraise the available SRs/MAs on the effects of IH protocols on physical performance across different fitness levels.

Methods A systematic search, aligned with the PRIOR (Preferred Reporting Items for Overviews of Reviews) guidelines, was conducted across seven electronic databases (PubMed/MEDLINE, Web of Science, Cochrane Database of Systematic Reviews, Scopus, Embase, PsycINFO, and Scielo) from inception to June 2025. Eligible studies included systematic reviews (SRs) with or without meta-analyses (MAs) or network meta-analyses (NMAs) evaluating the effects of intermittent hypoxia protocols on physical performance. Methodological quality was assessed using the AMSTAR-2 tool.

Results A total of 22 systematic reviews (14 with meta-analyses, 3 with network meta-analyses) analyzing 487 primary studies and 5,333 participants were included. Intermittent hypoxia (IH) protocols improved both aerobic and anaerobic performance, as well as muscular strength. Live high–train low (LHTL) and live low–train high (LLTH) protocols consistently enhanced $\dot{V}O_2\text{max}$, especially when combined with sea-level training. Anaerobic-focused strategies like repeated sprint training in hypoxia (RSH) and RSH induced by voluntary hypoventilation at low lung volume (RSH-VHL) led to improvements in sprint-fatigue resistance and glycolytic capacity. Intermittent hypoxic

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interval training (IHIT) and high-intensity interval training (HIIT) under hypoxia showed robust aerobic benefits. However, the magnitude of these effects varied depending on the type of protocol, training status, and hypoxic dose.

Conclusion IH is an effective and adaptable strategy to improve aerobic and anaerobic performance, as well as to enhance muscle strength and hypertrophy. These benefits often occur without consistent hematological changes. Future studies should focus on individualized approaches, standardization of terminology, and precise quantification of both hypoxic exposure and training load to optimize outcomes and ensure reproducibility.

Review registration: This overview was registered on the International Database of Systematic Review Protocols (PROSPERO ID: CRD42024465481).

Keywords Intermittent hypoxia, Physical performance, Elites, Subelites athletes, Hypoxic training, Altitude training

Introduction

Intermittent hypoxia (IH), characterized by alternating periods of low and normal or high oxygen levels, has evolved from being a hallmark of disease, including obstructive sleep apnea (OSA), to a pivotal therapeutic and performance-enhancing strategy. While chronic, uncontrolled IH leads to maladaptive outcomes such as systemic inflammation and cardiovascular dysfunction [1, 2], structured IH protocols leverage the principle of hormesis, whereby controlled hypoxic stressors activate cytoprotective pathways such as hypoxia-inducible factor 1 α (HIF-1 α) stabilization and enhanced antioxidant defenses [3, 4].

Broadly, altitude and hypoxic interventions are classified into three major paradigms based on the combination of exposure and training environment: Live High–Train High (LHTH), Live High–Train Low (LHTL), and Live Low–Train High (LLTH) (see Fig. 1) [5, 6]. Systemic hypoxia can be induced through two primary methods: by lowering barometric pressure, as seen in hypobaric hypoxia, or by decreasing the fraction of inspired oxygen (FiO₂) using techniques such as nitrogen dilution or oxygen filtration, known as normobaric hypoxia [7]. Although it remains debated whether different combinations of pressure and oxygen fraction elicit equivalent physiological effects [8–10], both approaches lead to a reduction in arterial oxygen saturation (SaO₂), which serves as a key stimulus for activating molecular signaling pathways involved in hypoxia-induced adaptations [11].

Historically, since the 1968 Olympic Games, living and training at altitude has gained popularity among endurance athletes seeking to boost aerobic capacity. To overcome the limitations of training under continuous hypoxia (LHTH)—which, in contrast to intermittent methods, involves sustained rather than alternating hypoxic exposure—the LHTL model emerged as a more refined approach. This model allows athletes to live at high altitude to stimulate physiological adaptations such as improved oxygen transport, ventilatory efficiency, and metabolic regulation, while training at lower altitudes to maintain high intensity [12]. This strategy was specifically

designed to avoid the detrimental effects of chronic hypoxia, including muscle mass loss, excessive fatigue, and impaired performance, which are more common in elite endurance athletes exposed to sustained hypoxaemia [6, 13].

Although LHTL is widely implemented and supported by several studies, its effectiveness in elite endurance athletes remains debated. Some authors argue that athletes with already high Hbmass approach a physiological “ceiling,” a concept derived from symmorphosis theory, which proposes that biological systems evolve to maintain structural and functional capacities precisely matched to maximal metabolic demands, thereby minimizing excess capacity under normal conditions [14]. From this perspective, additional hypoxic exposure in athletes near their physiological limits would induce minimal or no further gains in Hbmass or VO₂max [15–17]. In contrast, other researchers contend that, with adequate hypoxic dose and precise measurement methods, both hematological and performance improvements can still be observed [18–20].

With the advancement and increased accessibility of hypoxia-inducing technologies, such as normobaric hypoxic tents, chambers, and generators, training methodologies have evolved, popularizing more practical approaches like LLTH [5, 21]. This approach involves brief, intermittent exposures to hypoxic conditions, typically lasting less than two hours per session, 2–5 times a week, either at rest or during training activities [5]. The LLTH strategy encompasses a variety of protocols, each tailored to meet specific athletic goals, from enhancing endurance and aerobic capacity to improving strength and power output [5]. These protocols can be broadly categorized into passive and active, each offering distinct physiological and performance benefits (see Fig. 1) [5]. Despite varying in operational design, these protocols share the common goal of eliciting beneficial adaptations across metabolic, cardiovascular, respiratory, and neuromuscular systems. The effectiveness of these methods is supported by a complex interplay of physiological responses, including HIF stabilization, increased erythropoietin (EPO) production, enhanced mitochondrial

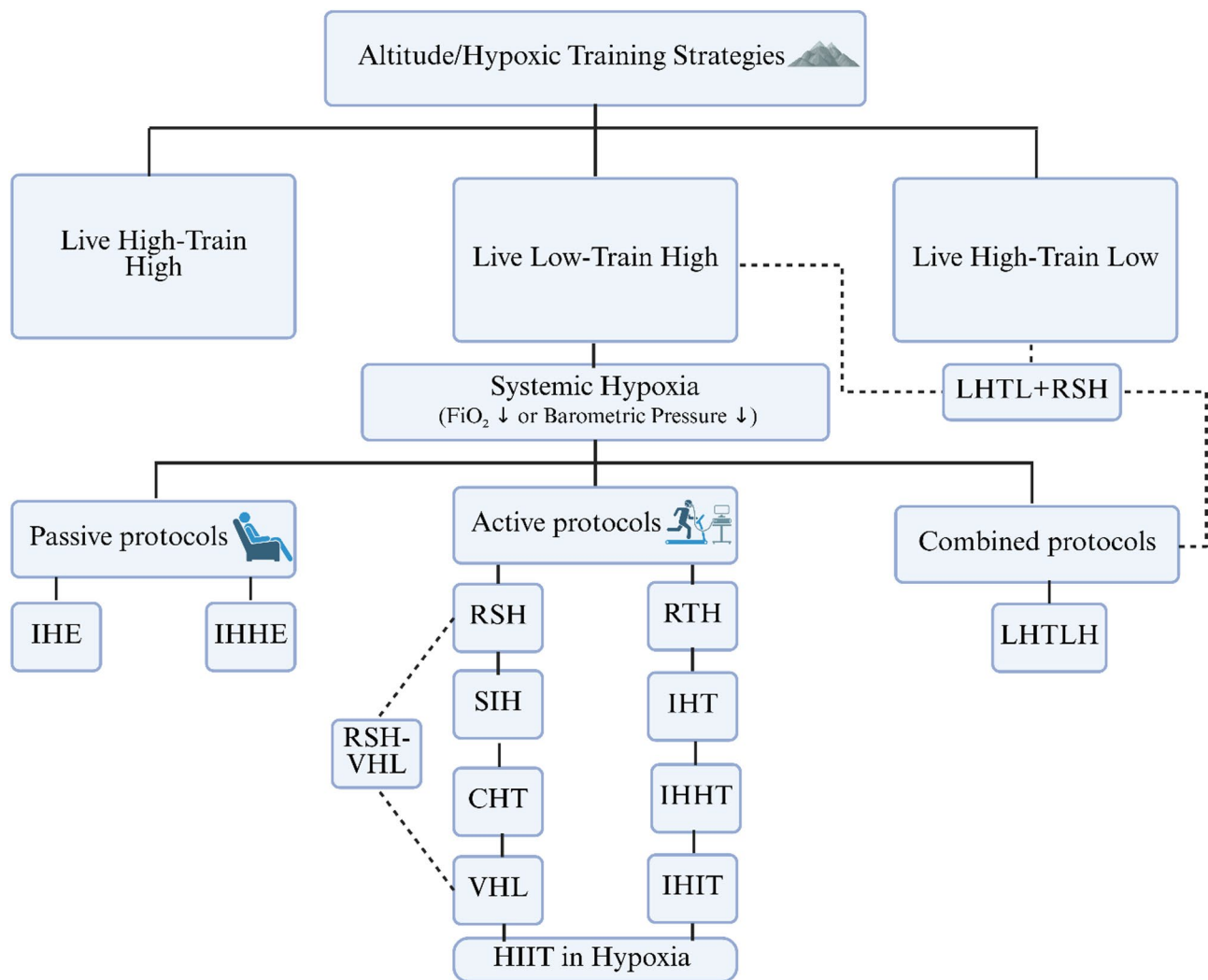


Fig. 1 Graphical panorama of major altitude/hypoxic training strategies. LLTH sub-modalities include passive and active protocols applied under systemic hypoxia. The combined protocol LHTLH represents a hybrid approach integrating LHTL with repeated sprint training in hypoxia (RSH) [5, 6, 26]

efficiency, and expanded vascularization, collectively improving oxygen delivery and utilization during physical exertion [5, 6, 22]. While passive IH may not directly enhance sea-level performance for elite athletes, it serves as an effective strategy for pre-acclimatization, preparing athletes and mountaineers for high-altitude endeavors, thus optimizing their physiological readiness and performance potential [15].

More recently, a combined approach, known as Live High–Train Low and High (LHTLH), has been proposed to leverage the complementary benefits of both LHTL and LLTH. Specifically, it combines prolonged altitude residence with high-intensity interval protocols in hypoxia, most notably Repeated Sprint Training in Hypoxia (RSH). This hybrid strategy aims to promote both aerobic and anaerobic adaptations and has shown promise in team-sport athletes, particularly by improving

repeated-sprint ability, a critical determinant of intermittent performance [6, 23].

In the last decade, an innovative IH approach known as Intermittent Hypoxia–Hyperoxia has emerged, blending phases of low oxygen levels with higher oxygen concentrations, characterized by a fraction of inspired oxygen (FiO₂) ranging from 0.30 to 0.40. Two applications are commonly distinguished: Intermittent Hypoxia–Hyperoxia Exposure (IHHE), involving passive exposure at rest, and Intermittent Hypoxia–Hyperoxia Training (IHHT), which specifically refers to exercise performed concurrently with hypoxia–hyperoxia breathing cycles. Notably, to date, no intervention study has investigated the chronic effects of intermittent hypoxia–hyperoxia breathing during exercise; current evidence is limited to acute crossover studies [24]. This method hypothesizes that alternating between hypoxic and hyperoxic states may enhance the body’s adaptive responses to

hypoxic stimuli through the upregulation of factors such as reactive oxygen species (ROS) and hypoxia-inducible genes, thereby potentially amplifying the physiological benefits of IH treatments [25]. This method may also improve exercise tolerance, as indicated by lower ratings of perceived exertion during IHHT. Recent years have witnessed exponential growth in empirical research investigating the effects of IH protocols on performance-related outcomes. This proliferation of clinical and experimental studies has driven a corresponding rise in systematic reviews (SRs), meta-analyses (MAs), and network meta-analyses (NMAs) seeking to appraise and synthesize this expanding evidence base. While traditional MAs compare the effectiveness of two interventions based on direct evidence, NMAs extend this approach by integrating both direct and indirect comparisons across multiple interventions within a single statistical framework. Although these reviews provide valuable insights into IH's potential, their findings remain highly heterogeneous, largely due to significant variability in methodological rigor, population focus, and outcome prioritization. Differences in IH protocols, including variations in hypoxic dose, exposure duration, modality (passive vs. active/hypobaric vs. normobaric), and frequency of sessions, further contribute to the fragmentation of conclusions across studies. Additionally, inconsistencies in study designs, control conditions, and outcome measures make direct comparisons between reviews challenging. This umbrella review aims to consolidate and critically appraise the current body of evidence from existing SRs and MAs that evaluate the effects of intermittent hypoxia on physical performance outcomes. By addressing methodological discrepancies and highlighting trends across intervention types and populations, this review provides a comprehensive synthesis of IH-based strategies for optimizing athletic performance.

Methods

This umbrella review was conducted following the Preferred Reporting Items for Overviews of Reviews (PRIOR) guidelines [27] and was registered within the International Prospective Register of Systematic Reviews (PROSPERO ID: CRD42024465481).

Search Strategy

A systematic literature search was conducted across seven electronic databases: PubMed/MEDLINE, Web of Science, Cochrane Database of Systematic Reviews, Scopus, Embase, and PsycINFO from inception to 1 June 2025 without applying any filters. The search strategy combined three main components: (1) exposure terms related to intermittent hypoxia and hypoxia training modalities, (2) study design filters targeting systematic reviews and meta-analyses, and (3) outcome-specific

terms related to *physical performance* (e.g., $\text{VO}_{2\text{max}}$, strength, hypertrophy). Synonyms and variants were combined using Boolean operators “AND” and “OR”. The detailed search string used in all databases is available in Table S1 (Supplementary Material).

Medical subject headings (MeSH) terms and wild-card options (i.e., truncated words, dollar sign) were used when appropriate. This search strategy was customized for each database's indexing system to ensure thorough literature retrieval. Detailed adaptations are provided in Table S1 of the supplementary material (SM). Manual verification of the references from selected papers was conducted to ensure a thorough search for pertinent studies. Additionally, on 04 June 2025, a search was performed on Google Scholar to identify any studies that might have been overlooked [28, 29]. However, given the large volume of search results, only the initial 100 records were examined [30].

Eligibility Criteria

Inclusion criteria were established based on the pre-defined PICOS/PECOS framework as follows:

Participants (P): Studies were included regardless of participants' age, sex/gender, or health status. **Intervention/Exposure (I/ E):** Systemic hypoxic training protocols within three established strategies: Live Low–Train High (LLTH), Live High–Train Low (LHTL), and the combined Live High–Train Low and High (LHTLH) approach [5]. LLTH protocols involve living at or near sea level while being intermittently exposed to hypoxia during rest or exercise sessions. These protocols induce systemic hypoxia through either normobaric or hypobaric means, and can be further classified according to their mode of application (Fig. 1):

- Passive modalities:
 - Intermittent Hypoxic Exposure (IHE).
 - Intermittent Hypoxia–Hyperoxia Exposure (IHHE).
- Active modalities:
 - Continuous Hypoxic Training (CHT).
 - Intermittent Hypoxic Training (IHT).
 - Intermittent Hypoxic Interval Training (IHIT).
 - Sprint Interval Training in Hypoxia (SIH).
 - Repeated Sprint Training in Hypoxia (RSH).
 - Resistance Training in Hypoxia (RTH).
 - Voluntary Hypoventilation at Low Lung Volume (VHL).
 - High-intensity interval training in hypoxia (HIIT).

This review focused exclusively on systemic hypoxia protocols. Local hypoxia methods (e.g., blood flow restriction or ischemic preconditioning) and chronic continuous exposure strategies without an intermittent component (e.g., LHTH) were excluded.

Comparison/Comparator (C): Studies comparing IH protocols to placebo, control, or alternative interventions (e.g., normoxia).

Outcomes (O): Studies assessing at least one performance-related outcome were considered.

Study Design (S): SRs, with or without MA, or NMA.

In our pursuit to summarize studies of the highest evidence level, we excluded grey literature and all review types other than SRs and MAs [31]. Additionally, we omitted original research studies with primary data, editorials, conference abstracts and posters, study and review protocol registrations, comments, commentaries, technical notes or reports, and letters from our overview. SRs that focused on animal studies were not deemed eligible for inclusion in the present review. Furthermore, studies examining pathological hypoxia, such as those investigating OSA, stroke, or other medical conditions associated with hypoxia, were excluded.

Study Selection

Duplicate entries were removed using EndNote software, followed by an independent screening of the search results by two authors (AB and AP) using predefined eligibility criteria and COVIDENCE systematic review software (Veritas Health Innovation, Melbourne, Australia, www.covidence.org). Discrepancies between the researchers were resolved through discussion or by consulting a third researcher, OD. Titles and abstracts that did not warrant immediate exclusion were subjected to a detailed full-text review to ascertain their inclusion in the study.

Data Extraction

Both investigators (AB and AP) independently carried out the data extraction process using a specifically designed Excel spreadsheet to organize and standardize the collected information. The data extracted from each SR included the following elements: first author, year and country of publication, review type, electronic databases searched, primary study type, number of included primary studies, publication date range, quality assessment tool used, type of intervention, and population characteristics (age, sex/gender, health status, cognitive status) to provide context for the study populations. For SRs including MAs or NMAs, additional statistical data were collected, including the sample size for each assessed outcome, effect size, the equation used to compute effect size, significance levels (p-values), and measures of heterogeneity (χ^2 tests, 95% confidence intervals [CIs], and I^2

values). Finally, the main results reported in each SR were extracted to synthesize key findings across studies.

Overlap of the Included Studies

To quantify the degree of overlap among the included SRs, we employed the Corrected Covered Area (CCA) index methodology [32]. This approach involves creating a citation matrix where primary studies are listed row-wise, and the SRs are listed column-wise. This matrix aids in determining the frequency of each primary study's citation across the SRs. The CCA index is computed using the formula:

$$CCA = \frac{N - r}{r \cdot c - r}$$

where N represents the total count of primary publications cited across the reviews (accounting for repetitions), r is the number of unique primary publications, and c is the total number of SRs included in the umbrella review. The CCA's value categorizes the extent of overlap as follows: a CCA of 0%–5% indicates slight overlap, >5%–10% suggests moderate overlap, >10%–15% denotes high overlap, and a CCA >15% signifies a very high overlap. To refine our analysis and align with recent methodological recommendations [32], we also adjusted the CCA by stratifying based on publication year of the SRs. This was done to account for differences in publication timelines that could influence overlap. The overlap analyses were conducted using the ccaR package in the R environment [33].

Methodological Quality Evaluation

The methodological quality of the included SRs was independently evaluated by two investigators (AB and NLB), using “Assessing the Methodological Quality of Systematic Reviews” revised version (AMSTAR-2) [34]. The AMSTAR-2 checklist, a validated and reliable tool, evaluates the methodological quality of SRs. It consists of 16 distinct domains with 7 items considered as critical (2,4,7,9,11,13, and 15). The AMSTAR-2 assessment results in four possible quality ratings: ‘High’ - zero or one non-critical weakness; ‘Moderate’ - more than one non-critical weakness; ‘Low’ - one critical flaw with or without non-critical weaknesses; and ‘Critically low’ - more than one critical flaw with or without non-critical weaknesses [34]. In the case of disagreements, the two reviewers engaged in discussions to resolve, and if consensus remained elusive, a third reviewer (OD) was brought in for consultation.

Data Synthesis

Data extracted from the included SRs, with or without MA or NMA, were synthesized narratively. This narrative

synthesis was, then, concisely presented in summary tables.

Inter-Rate Agreement

Inter-rater agreement was evaluated using Cohen's kappa during key phases: screening, data extraction, and quality assessment, ensuring consistency and reliability across the raters' decisions. The following formula was used: $\kappa = (P_o - P_e)/(1 - P_e)$, where " P_o " represents the observed agreement among raters, and " P_e " is the hypothetical probability of chance agreement. Values of " κ " range from -1 (complete disagreement) to 1 (perfect agreement).

Protocol Deviations

The main deviation from our protocol (PROSPERO ID: CRD42024465481) was the inclusion of NMAs, which was not initially specified. This decision was made to enhance the comprehensiveness of our synthesis, as NMAs allow for the comparison of multiple interventions by integrating both direct and indirect evidence. Given the increasing use of NMAs in IH research, their inclusion provided a more complete and nuanced understanding of protocol effectiveness and ranking.

A second deviation concerned the scope of the outcomes assessed. While the original protocol planned to evaluate both health-related and physical performance outcomes, the large number of eligible studies identified during the screening process led to a strategic decision to

split the review into two parts. This first umbrella review focuses solely on physical performance outcomes, while a second publication will address the health-related outcomes, allowing for more focused analyses and clearer interpretation of findings in each domain.

Results

Search Results

Initially, our comprehensive database search yielded 381 potential articles, broken down as follows: 93 from PubMed/MEDLINE, 107 from Embase, 58 from Scopus, 117 from Web of Science, 2 from the Cochrane Database of Systematic Reviews, 4 from PsycINFO, and 0 from Scielo. After removing duplicates, 257 studies remained for a preliminary screening based on their titles and abstracts. This screening process led to the selection of 40 papers for full-text evaluation, ultimately resulting in 20 articles meeting our inclusion criteria and being incorporated into the final analysis. Additionally, two relevant articles were identified through manual searching, bringing the total number of included studies to 22. The agreement in the study selection process was high at the title and abstract screening stage ($\kappa=0.8$) and perfect at both the full-text review stage and within the Google Scholar search process ($\kappa=1$). The complete study selection process is presented in Fig. 2. A detailed list of reasons for excluding papers is documented in Appendix A of the Supplementary Material.

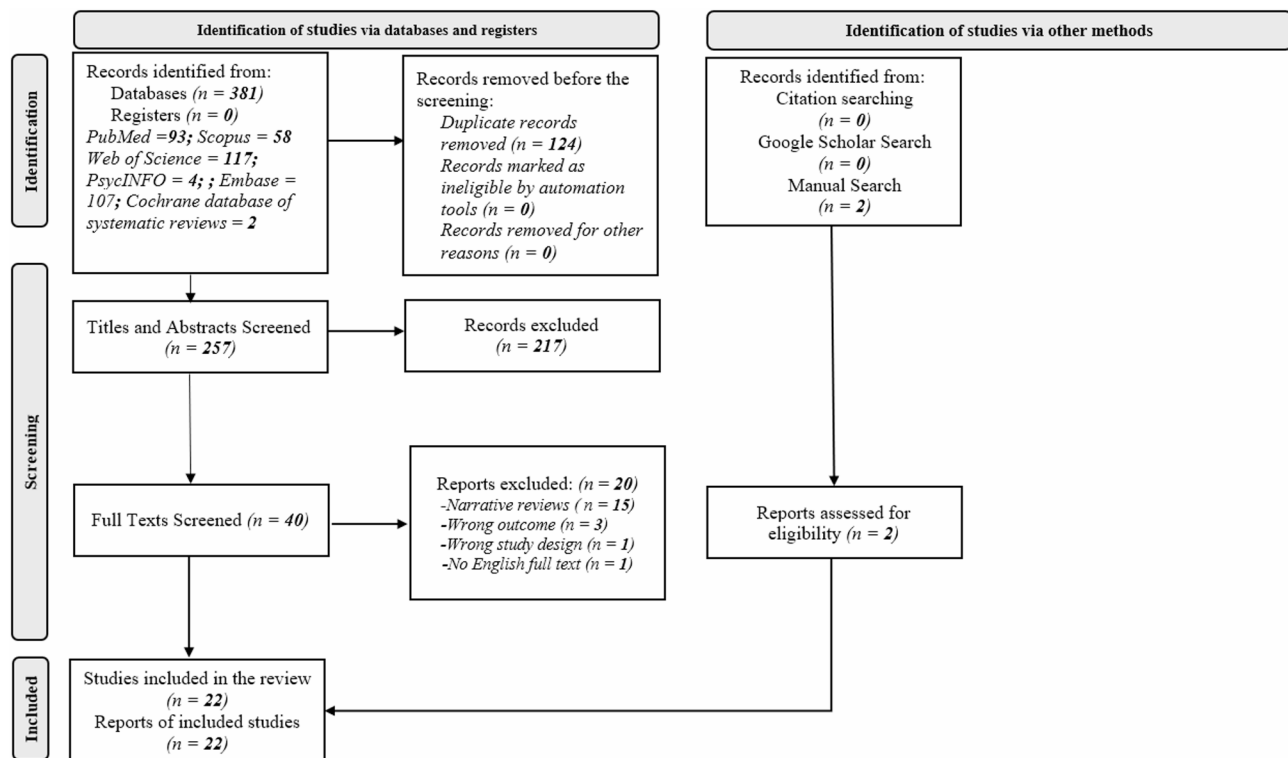


Fig. 2 Study selection process. SR: Systematic Review, MA: Meta-Analyses, NMA: Network Meta-Analyses

Study Characteristics

The publication timeframe of the 22 included SRs spanned from 2009 to 2025 [11–54]. Of these, 14 incorporated MAs and three included NMAs [45–47]. The SRs encompassed diverse methodological designs: eight focused exclusively on randomized controlled trials (RCTs), four combined RCTs with non-randomized controlled trials, and the remainder included pilot, crossover, or quasi-experimental studies. In total, the SRs analyzed 487 unique primary studies comprising 5,333 participants. The number of included studies per SR ranged from 5 to 59, covering research conducted between 1988 and 2025. Participants ranged in age from 13 to 67 years. Most reviews searched between two and five databases, with PubMed being the most frequently used source.

The populations studied encompassed a wide range of training statuses, including untrained individuals, recreationally active participants, sub-elite, and elite athletes. Male participants were consistently overrepresented across the reviews. A broad spectrum of hypoxic protocols was examined, incorporating both hypobaric and normobaric conditions via natural altitude exposure or simulated environments such as hypoxic chambers and breathing devices. These protocols included LHTL, LHTLH, and LLTH, as well as HIIT conducted under hypoxic conditions. LLTH protocols were the most frequently represented, identified in 18 of the 24 included systematic reviews. While certain reviews focused exclusively on LLTH interventions, others encompassed a broader range of hypoxic training modalities, including LHTL and LHTLH, which were examined in 5 and 2 reviews, respectively. The hypoxic intensity, expressed as FiO_2 , ranged from 10% to 17%, or simulated altitudes of 690 m to 6875 m. Training frequencies ranged from 2 to 7 sessions per week, with total durations extending from 1 week to 13 weeks and total sessions ranging from 5 to 56. Further details regarding the distribution of protocols and population characteristics across the reviews are provided in Table 1.

Effects of Intermittent Hypoxia Protocols on Physical Performance

IH protocols demonstrated overall beneficial effects on physical performance across trained and untrained individuals. Significant improvements were observed in key performance outcomes, including aerobic and anaerobic performance metrics, muscular strength, exercise tolerance, and repeated-sprint ability (Table 2). However, the extent of these benefits varied depending on the type of protocol used, the training status of participants, and the methodological characteristics of the studies reviewed.

Improvements in aerobic performance, particularly $\text{VO}_{2\text{max}}$ and time to exhaustion, were consistently reported across various hypoxic training protocols. Among them, live high–train low (LHTL) protocols combined with low-altitude training yielded the largest effects (Standardized Mean Difference [SMD] = 1.04, 95% Confidence Interval [CI] [0.47, 1.61]), followed by simulated altitude training (SMD = 0.91, 95% CI [0.44, 1.38]) [45, 47]. RSH, as a form of LLTH, also led to significant $\text{VO}_{2\text{max}}$ gains in athletes (SMD = 0.76, 95% CI [0.29, 1.23]) [47]. Brocherie et al. [41] reported enhanced Repeated Sprint Ability (RSA) under RSH compared to RSN (SMD = 0.46, $p = 0.05$), although $\text{VO}_{2\text{max}}$ improvements under RSH were less consistent (SMD = 0.18, $p = 0.41$). A NMA ranked intermittent hypoxic interval training (IHIT) as the most effective protocol for improving $\text{VO}_{2\text{max}}$, with a Surface Under the Cumulative Ranking (SUCRA) probability of 42% [47]; however, this ranking was based on a single review, which included only one small study ($n = 11$), so these findings should be interpreted with caution. SUCRA values, expressed as percentages, reflect the probability that a given intervention ranks among the most effective options, where 0% indicates the worst and 100% the best. These values are derived from cumulative ranking probabilities in NMA and offer a relative, not absolute, measure of comparative effectiveness. Similarly, Feng et al. [46] reported significant improvements in aerobic (SMD = 0.78) and anaerobic (SMD = 0.97) performance under intermittent hypoxic conditions compared to normoxia in athletes from diverse training backgrounds who had not recently been exposed to hypoxia. Among different training modalities, long-term high-intensity interval training (L-IHT) and RSH demonstrated the most pronounced effects on performance. Feng's NMA also highlighted that the dose–effect characteristics of the protocols may be influenced by the potential negative consequences of chronic hypoxia, which could partly explain the variability in their outcomes [45].

However, while the effects of RSH and IHIT appear promising, findings are not uniformly favorable across studies. Zelenovic et al. [43] reported significant gains in maximum and mean power during repeated sprint tests under RSH, though these were not always superior to normoxic equivalents. Conversely, Deb et al. [49] in a review focusing exclusively on the acute effects of hypoxia, reported marked performance decrements during single-session exposures, particularly in prolonged efforts exceeding 10 min ($-26.8\% \pm 5.5\%$). Importantly, these acute fatigue responses should not be interpreted as evidence against training-induced benefits. Rather, they underscore that the immediate performance decline under hypoxia constitutes a potent physiological stressor that, when appropriately managed across repeated

Table 1 Overview of descriptive characteristics for the included reviews

Reference	Review type	Databases searched	Nº of included primary studies	Primary study design	Search period	Publication range	Quality assessment tool used	Total participants across the review	Nº of cases/controls	Age (years)	Participants	Intervention (modality/frequency)	Altitude (m)/FIO ₂ (%)/SpO ₂
Behrendt et al. [11]	SR	PubMed, WoS, Scopus, Cochrane Library	8	5 RCT, 1 NRS, 2 Pilot studies	From Jan 2000 to Sep 2021	2017–2021	Downs & Black	304 (only 34 athletes)	15/19	18–20	Athletes with and without overtraining syndrome	- Normobaric IHHE -5 weeks -3 sessions/ week IHHE - one 60-min session	10%-35%
Uzun et al. [35]	SR	PubMed, Elsevier, Cochrane, PEDro	16	2 NRS, 9 RCTs, 2 Pilot studies, 3 Randomized not controlled	NR	2004–2022	NR	537 (only 11 athletes)	NR	21.4±0.3	Male Athletes	LLTH (NA) -9 days to 8 weeks -3 to 7 sessions/week -Hypobaric and Normobaric LLTH -1 to 7 weeks -2 to 7 sessions/week Natural LHTL / Artificial LHTL/ Brief Intermittent -NR -Total 14–39 sessions -Normobaric LLTH(RTH) -3 to 8 weeks -2 to 4 sessions/week	10%-35%
Huang et al. [36]	SR&MA	PubMed, Embase, Cochrane Library, WoS	19	RCTs	From Jan 2000 to Jan 2023	2001–2020	Cochrane for RoB	349	169/180	15–29	Athletes	LLTH (NA) -9 days to 8 weeks -3 to 7 sessions/week -Hypobaric and Normobaric LLTH -1 to 7 weeks -2 to 7 sessions/week	2500 m -5900 m 11.7%-17%
McLean et al. [21]	SR	PubMed, SPORTDiscus, Embase, WoS	40	NR	From inception to Dec 2013	1988–2014	NR	605	350/255	19–44	Athletes	Natural LHTL / Artificial LHTL/ Brief Intermittent -NR -Total 14–39 sessions -Normobaric LLTH(RTH) -3 to 8 weeks -2 to 4 sessions/week	1956 m-5500 m 12.7%-16%
Lancaster and Smart. [37]	SR&MA	PubMed	11	RCTs	From inception to July 2010	1997–2010	Cochrane for RoB	160	160	N26.7 ± 9.9 /H26.2 ± 9.1	Athletes	Normobaric LLTH -1 to 13 weeks -3 to 7 sessions/week Normobaric LLTH -4 to 12 weeks -2 to 4 sessions/week Normobaric LLTH(RSH) -3.7 ± 1.3 weeks -2.6 ± 0.6 sessions/ week	10%-17% NR 2900 m -3500 m
Benavente et al. [38]	SR&MA	PubMed, WoS, SPORTDiscus, and the Cochrane Library	17	RCTs	From inception to June 2022	2003–2020	Cochrane for RoB and the PEDro scale	348	184/164	20–29	Athletes	Normobaric LLTH -4 to 12 weeks -2 to 4 sessions/week Normobaric LLTH(RSH) -3.7 ± 1.3 weeks -2.6 ± 0.6 sessions/ week	NR 2900 m -3500 m
Albertus-Cámara et al. [39]	SR	PubMed, SPORTDiscus, Cochrane Library, Scopus and PEDro	12	7 RCTs / 5 quasi-experimental	From inception to Dec 2021	2004–2020	PEDro	202	NR	19–33	Athletes	Normobaric LLTH -1 to 13 weeks -3 to 7 sessions/week Normobaric LLTH -4 to 12 weeks -2 to 4 sessions/week Normobaric LLTH(RSH) -3.7 ± 1.3 weeks -2.6 ± 0.6 sessions/ week	10%-17% NR 2900 m -3500 m
Gamonalles et al. [40]	SR	PubMed, Science Direct, and WoS	19	NR	2000- April 2021	2013–2020	NR	527	NR	19–67	Trained & untrained	Normobaric LLTH -4 to 12 weeks -2 to 4 sessions/week Normobaric LLTH(RSH) -3.7 ± 1.3 weeks -2.6 ± 0.6 sessions/ week	NR 2900 m -3500 m
Brocherie et al. [41]	SR&MA	PubMed, SPORTDiscus, ProQuest, and WoS	9	RCTs	From inception to July 2016	2013–2015	NR	202	103/99	26 ± 12	Athletes	Normobaric LLTH -4 to 12 weeks -2 to 4 sessions/week Normobaric LLTH(RSH) -3.7 ± 1.3 weeks -2.6 ± 0.6 sessions/ week	2900 m -3500 m
Seitz et al. [42]	SR	PubMed and WoS	12	NR	From inception to June 2019	2001–2019	NR	259	126/133	NR	Trained /untrained	Normobaric LLTH (cycling and running) -3 to 8 weeks -2 to 5 sessions/week LLTH(RSH) -2 to 6 weeks -Total 5 to 18 sessions LLTH (RTH) -4 to 8 weeks -2 to 3 sessions/week LLTH(RSH)-ISH-IHE-Continuous and Interval training under Hypoxia-HIT (NR) -3 to 8 weeks -2 to 7 sessions/week Hypobaric and Normobaric LHTL, LHTH, and IHT -Total 12 to 56 sessions Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	2100 m-4500 m 13%-14.6% 12%-16% 1850 m-6875 m 690 m-5500 m 690 m - 5500 m
Zelenovic et al. [43]	SR	Google Scholar, PubMed, WoS, and ResearchGate	14	Parallel design	2000–2021	2013–2020	NR	347	NR	15.3–35	Athletes	LLTH(RSH) -2 to 6 weeks -Total 5 to 18 sessions LLTH (RTH) -4 to 8 weeks -2 to 3 sessions/week LLTH(RSH)-ISH-IHE-Continuous and Interval training under Hypoxia-HIT (NR) -3 to 8 weeks -2 to 7 sessions/week Hypobaric and Normobaric LHTL, LHTH, and IHT -Total 12 to 56 sessions Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	13%-14.6% 12%-16% 1850 m-6875 m 690 m-5500 m 690 m - 5500 m
Ramos-Campo et al. [44]	SR&MA	PubMed, WoS, and the Cochrane Library	9	NR	From inception to June 2017	2003–2016	Cochrane for RoB	158	ALL	21–28	Trained/untrained	LLTH (RTH) -4 to 8 weeks -2 to 3 sessions/week LLTH(RSH)-ISH-IHE-Continuous and Interval training under Hypoxia-HIT (NR) -3 to 8 weeks -2 to 7 sessions/week Hypobaric and Normobaric LHTL, LHTH, and IHT -Total 12 to 56 sessions Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	12%-16% 1850 m-6875 m 690 m-5500 m 690 m - 5500 m
Feng et al. [46]	SR&NMA	PubMed, WoS, Embase, EBSCO, and Cochrane Library	56	RCTs, NRS, Crossover	From inception to June 2023	2002–2023	PEDro	1040	543/497	NR	Trained	LLTH(RSH)-ISH-IHE-Continuous and Interval training under Hypoxia-HIT (NR) -3 to 8 weeks -2 to 7 sessions/week Hypobaric and Normobaric LHTL, LHTH, and IHT -Total 12 to 56 sessions Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	1850 m-6875 m 690 m-5500 m 690 m - 5500 m
Feng et al. [45]	SR&NMA	WoS, PubMed, Embase, and EBSCO	59	RCTs and NRS	From inception to Feb 2023	1996–2022	Cochrane for RoB	1821	1327/494	NR	Athletes	Hypobaric and Normobaric LHTL, LHTH, and IHT -Total 12 to 56 sessions Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	690 m-5500 m 690 m - 5500 m
Yu et al. [47]	SR&NMA	PubMed, WoS, SPORTDiscus, ProQuest Central, and Cochrane Library	42	RCTs and NRS	From inception to March 2023	1996–2022	Cochrane for RoB	1246	ALL	18–35	Athletes and untrained	Normobaric and Hypobaric / LHTL and LLTH (IHE/IHT/ IHT, RSH, RTH) -Total 10 to 56 sessions	690 m - 5500 m

Table 1 (continued)

Reference	Review type	Databases searched	Nº of included primary studies	Primary study design	Search period	Publication range	Quality assessment tool used	Total participants included across the review	Nº of cases/controls	Age (years)	Participants	Intervention (modality/frequency)	Altitude (m)/FIO ₂ (%)/SpO ₂
Westmacott et al. [48]	SR&MA	PubMed, Science Direct, and SPORTDiscus	9	RCTs and NRIS	From inception to Feb 2021	1998–2020	PEDro scale	194	ALL	20–29	Athletes and untrained	Hypobaric and Normobaric HIIT under hypoxia -2 to 13 weeks -NR	12,6%-15.3%
Dab et al. [49]	SR&MA	GoogleScholar, PubMed, and SPORTDiscus	53	RCTs	From inception to April 2017	1990–2017	NA	798	ALL	>18	Athletes	Normobaric and Hypobaric LLTH -Total of 1 to 3 sessions	500 m -5700 m
Hamlin et al. [50]	SR&MA	PubMed, Medline, WoS, SPORTDiscus	10 (only 8 in MA)	RCTs	From inception to Sep 2016	2005–2016	NA	187	ALL	15–23	Athletes	LHTL, LHTLH, and LLTH (IHT, IHE, RTH and RSH) -1 to 5 weeks -1 to 7 sessions/week	2500 m-4650 m
Précart et al.[51]	SR&MA	PubMed/MEDLINE, SPORTDiscus, ProQuest, and Web of Science	10	RCTs	From inception to Feb 2025	2016–2025	PEDro scale	199	ALL	22±7	Trained	LLTH (RSN, RSH-VHL) -2 to 6 weeks -2 to 3 sessions/week	SpO ₂ 78.5–94.6
Bonetti and Hopkins [55]	SR&MA	PubMed, SPORTDiscus, and Google Scholar	51	RCTs, NRIS, and crossover	From inception to April 2007	1994–2007	NA	638	NR	NR	Elite and subelite athletes	LLTH, LHTL -5 days to 47 days	1800 m-6000 m
Yu et al. [53]	SR	PubMed, Google Scholar, EMBASE, WOS and Cochrane Library	5	RCTs	From Nov 2013 to Nov 2023	2014–2019	Cochrane for RoB	134	67/67	20–46	Cyclist athletes	LLTH -1 to 6 weeks -1 to 4 sessions/week	1200 m-4000 m
Fentaw et al.[54]	SR&MA	PubMed, Science Direct, Europe PMC, ProQuest, and the Cochrane Library	6	RCTs	From inception to Jan 2025	1997–2022	PEDro	116	61/55	18–42	Distance runners	HIIT under hypoxia	2700 m-3000 m

WoS: Web of Science, RCT: Randomized Controlled Trial, Obs: observational studies, NRIS: Non-Randomized Interventional Study, NA: Not Available, NR: Not Reported, IHE: Intermittent Hypoxia Exposure, IHT: Intermittent Hypoxia Training, IHHE: Intermittent Hypoxia-Hyperoxia Exposure, IHHT: Intermittent Hypoxia-Hyperoxia Training, LLTH: Live Low-Train High, RTH: Resistance Training in Hypoxia, RSH Repeated Sprint Training in Hypoxia, HIIT: High Intensity Interval Training, RSN: Repeated sprint training with Normal breathing CIM: Cognitive Impairment, SR: Systematic Review, MA: Meta-Analyses, RoB: Risk of Bias, T2DM: Type 2 diabetes mellitus

Table 2 Summary of assessed outcomes and main results of the included reviews

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Behrendt et al. [11]	n.a	n.a	NR	Exercise tolerance (measured as time to exhaustion, VO ₂ peak, VO ₂ at the first ventilatory threshold, physical work capacity, functional capacity (measured by the six-minute walk distance))	IHHE ↑ exercise tolerance (time to exhaustion) at post-intervention and 1-month follow-up vs. sham IHHE ↑ peak VO ₂ • + 12.6% in older CAD patients (14.3 → 16.1 ml·min ⁻¹ ·kg ⁻¹) • + 43.2% in cardiology outpatients (13.9 → 19.9 ml·min ⁻¹ ·kg ⁻¹) • + 26.1% in older CAD patients (13.4 → 16.9 ml·min ⁻¹ ·kg ⁻¹) IHHE ↑ VO ₂ at ventilatory threshold • + 11.3% (11.5 → 13.8 ml·min ⁻¹ ·kg ⁻¹) IHHE > sham IHHE for peak VO ₂ improvements IHHE ↑ PWC170 in young athletes with overtraining syndrome IHHE + multimodal training → ↑ 6-min walk distance > sham IHHE + multimodal training
Uzun et al. [35]	n.a	n.a	NR	Muscle damage, muscle recovery	IHHE ↓ muscle damage markers IHHE ↑ muscle recovery after heavy resistance exercise in male athletes
Huang et al. [36]	IHT on VO ₂ max WMD = 3.20 IHT on Hb WMD = 0.25 (1.33 ~ 5.08/ 0.04 ~ 0.45, NR)	IHT on VO ₂ max = 76.6% / IHT on Hb = 59.4% (NR, p = 0.000 / p = 0.002)	NR	VO ₂ max and Hb	-LLTH in athletes: ↑ oxygen uptake (MD = 3.20), ↑ hemoglobin (MD = 0.25) -LLTH: ↑ aerobic capacity across sports disciplines
Mclean et al. [21]	n.a	n.a	NR	Physical performance	-LLTH modes: Interval, continuous, repeated sprint, resistance training -Training diversity: Variations in modes/intensities affect outcomes -Methodological considerations: Importance of matching training intensities between hypoxic/normoxic conditions -Concerns: Matching absolute intensities ↑ relative intensity in hypoxia -Majority findings: ↔ additional benefits of hypoxic vs. normoxic training -Observed benefits: ↑ high-intensity, anaerobic performance (e.g., interval, repeated sprint training)
Lancaster and Smart. [37]	VO ₂ max WMD = 1.51 (0.44, 2.58) p = 0.006 / Serum Hb WMD = 0.57 (0.38, 0.75) p = 0.00001 / HRmax = WMD - 1.77 (-3.03, -0.50) p = 0.006 / HEMATOCRIT WMD = 0.60 (-0.69, 1.88) p = 0.36 / PEBLC WMD = -3.03 (-4.57, -1.49) p = 0.00001	VO ₂ max I ² = 59% / Serum Hb I ² = 34% / HRmax I ² = 45% / HEMA-TOCRIT I ² = 0% / PEBLC I ² = 63%	NR	Performance: VO ₂ max, serum Hb, max HR, hematocrit, PEBLC	-VO ₂ max: ↑ VO ₂ max (p = 0.006) in hypoxic vs. normoxic groups. ↑ VO ₂ max in studies with ≥ 9.5 h/day exposure (p = 0.03) -Hb: ↑ Serum Hb (p < 0.00001) in hypoxic vs. normoxic groups -HRmax: ↓ HRmax (WMD = -1.77 beats·min ⁻¹ , p = 0.006) in hypoxic vs. normoxic groups -Hematocrit: ↔ Serum hematocrit (WMD = 0.60%, p = 0.36) between hypoxic and normoxic groups -PEBLC: ↓ Peak lactate (p = 0.0001) in hypoxic vs. normoxic groups

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Benavente et al. [38]	Muscle hypertrophy SMD=0.21 (-0.05–0.47) p=0.06/ Lean mass SMD=0.02 (-0.17 to 0.21) p=0.87/ Strength development SMD=0.13 (-0.00; 0.27) p=0.11/ Muscle thickness SMD=0.06 (-0.69; 0.57) p=0.87	Muscle hypertrophy I ² =16.3/ Lean mass I ² =0/ Strength development I ² =13.2/ Muscle thickness I ² =77.4	NR	Muscle hypertrophy and strength development	-RTH & Muscle Hypertrophy: ↑ CSA under moderate hypoxia with moderate loads and short inter-set rest intervals ↔ Lean mass and muscle thickness across conditions (RTH vs. RTN) -RTH & Strength Development: ↑ 1RM with long inter-set rest intervals (≥ 120 s) and moderate loads ↔ 1RM between severe hypoxia and normoxia (trivial differences) -General Trends: ↑ Small to medium benefits with moderate hypoxia and moderate loads for strength and CSA ↔ No consistent effect on lean mass or muscle thickness
Albertus-Cámara et al. [39]	n.a	n.a	NR	Performance and hematological parameters	Hematological Parameters ↔ Hb concentration (short exposures insufficient for improvement) ↑ Hb concentration (long exposures ≥ 14 h/day) ↔ Reticulocyte percentage (temporary increases not sustained post-intervention) ↓ SpO ₂ during hypoxia interventions ↑ EPO during long exposures (≥ 14 h/day) Sports Performance ↑ Time to exhaustion (short exposures < 3 h effective) ↔ 3000 m run time (no significant improvement in most studies) Training and Exposure Conditions ↔ Effectiveness of hypoxia state (similar outcomes at rest or during exercise) ↑ Time to exhaustion with HIIT under hypoxia
Gamonales et al. [40]	n.a	n.a	NR	Strength and muscular hypertrophy	-Muscle Strength ↑ Strength improvements: Resistance training in hypoxia significantly increased muscle strength in most studies ↔ Normoxia vs. Hypoxia: Some studies found no statistically greater benefit than normoxia Best results: Observed with moderate intensity (50–70% 1RM), 4–8 weeks of training, 3–4 sets, and 6–15 repetitions -Muscle Hypertrophy ↑ Hypertrophy improvements: Positive changes in muscle size were reported in most studies using hypoxic training ↔ Normoxia vs. Hypoxia -Optimal protocols: Moderate load (50–70% 1RM) Interventions lasting 4–7 weeks Inclusion of upper and lower body exercises
Brocherie et al. [41]	RSA SMD=0.46 (-0.02–0.93) p=0.05/ VO ₂ max SMD=0.18 (-0.25–0.61) p=0.41	RSA I ² =6.19% /VO ₂ max I ² =0.00%	NR	RSA and VO ₂ max	Mean Repeated-Sprint Performance ↑ RSA compared to RSN (P=0.05) Best Repeated-Sprint Performance ↔ RSA compared to RSN (P=0.30) VO ₂ max ↔ VO ₂ max compared to RSN (P=0.41)

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Seitz et al. [42]	n.a	n.a	NR	Endurance capacity	-VO ₂ Peak: H: ↑ in 6 studies/ N: ↑ in 4 studies -VO ₂ at Second Ventilatory Threshold: H: ↑ across all 6 studies/ N: ↑ in only 1 study -Maximum Ventilation: H: ↑ in 3 of 5 studies/ N: ↑ in 1 study -HRmax: H: ↓ in 2 studies/ N: ↔ -Respiratory Exchange Ratio: H: ↑ in 1 study -Hematological Variables: Hb, Hematocrit, and Erythrocyte Count: ↔ in both H and N groups across studies Maximum Lactate H: ↑ in 1 study/ N: Mixed results with minor changes Performance Variables: Time to Exhaustion: H: ↑ in 2 studies/ N: ↑ in 2 studies Maximum Wattage: H: ↑ in 5 studies/N: ↑ in 3 studies Wattage at VO ₂ VT ₂ : H: ↑ across all 3 studies/ N: ↑ in 1 study
Zelenovic et al. [43]	n.a	n.a	NR	Performance	-Repeated Sprint Ability Total Time RSH: ↓ (1.0–3.6% improvement) RSN: ↔ or ↓ (-1.7 to -1.9%) Number of Sprints to Exhaustion: RSH: ↑ (20–64% improvement) RSN: ↔ (no significant changes) Distance Traveled: RSH: ↑ (+15.1 m improvement) RSN: ↑ (+6.5 m improvement) Between Groups: ↔ -Power Output Maximum Power: RSH: ↑ (4.7–29% improvement) RSN: ↑ (1.5–26% improvement) Mean Power (RSAm _{ean}): RSH: ↑ (6.4% improvement in some studies) RSN: ↑ (larger improvements in certain studies) -Aerobic Performance Wingate Test: Maximum Power (Wmax30s): RSH: ↑ (15% improvement in one study) RSN: ↔ (no significant differences) Mean Power (Wmean30s): RSH: ↑ (2.7% improvement) RSN: ↑ (5% improvement) -VO ₂ max: RSH: ↑ (progress in 6–8%, not always significant) RSN: ↑ (similar improvements) Yo-Yo Tests (YYIR1 and YYIR2): RSH: YYIR1: ↑ (+33% improvement in one study) YYIR2: ↔ (no significant improvement compared to RSN)

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Ramos-Campo et al. [44]	CSA H: SMD=0.70 (0.05, 1.35) p=0.04 / CSA (H vs N): SMD=0.24 (-0.19, 0.68) p=0.27 / Lean Mass H: SMD=0.37 (-0.13, 0.88) p=0.15 / Lean Mass (H vs N): SMD=-0.05 (-0.56, 0.46) p=0.84 / Overall Muscle Strength SMD=1.88 (1.20, 2.56) p<.00001 / Strength gains (H vs N): SMD=0.20 (-0.27, 0.78) p=0.23	CSA (H): I ² =37% / CSA (H vs N): I ² =0% / Lean Mass (H): I ² =0% / Lean Mass (H vs N): I ² =0% / Overall Muscle Strength (H vs N): I ² =0%	NR	Performance (strength and muscle growth)	-CSA Within Groups (H): ↑ post-training (p=0.04) Between Groups (H vs. N): ↔ in CSA changes (p=0.27) -Lean Mass Within Groups (H): ↔ post-training (p=0.15) Between Groups (H vs. N): ↔ in lean mass changes (p=0.84) -Muscle Strength Within Groups (H): ↑ in strength: Lower limbs: (p=0.0001) Upper limbs: (p=0.0004) Overall strength improvement (↑): (p<.00001) Between Groups (H vs. N): ↔ in strength gains (p=0.23)
Feng et al. [46]	Aerobic Performance (I-IHT): SMD=0.78 (0.52–1.05) / Aerobic Performance RSH: SMD=0.30 (0.10–0.50) / Anaerobic Performance (I-IHT): SMD=0.97 (0.12–1.81) / Anaerobic Performance RSH: SMD=0.32 (0.05–0.59) Global inconsistency for aerobic performance: p=0.6774 Global inconsistency for anaerobic performance: p=0.7037	Aerobic performance: I ² =8% / Anaerobic performance: I ² =20.5%	NR	Performance	Aerobic Performance ↑ I-IHT vs N ↑ RSH ↔ Other Modes (ISH, s-IHT, IHE, CHT, C+I) Anaerobic Performance ↑ I-IHT: Greatest improvement among all modes ↑ RSH ↑ ISH and s-IHT: compared to normoxic training ↔ IHE and CHT Overall Observations ↔ Passive hypoxic methods (IHE) and continuous low-intensity training (CHT) ↔ Combined training (C+I)
Feng et al. [45]	LHTL combined with low altitude training: SMD=1.04 (0.47–1.61) LHTL combined with simulated altitude training: SMD=0.91 (0.44–1.38) LHTH: SMD=0.61 (0.26–0.96) ↑ IHT: SMD=0.36 (0.10–0.62) IHE: SMD=0.09 (-0.24–0.41) HHL: SMD=0.17 (-0.44–0.77)	I ² =46.2%	NR	Performance (VO ₂ max)	VO ₂ max: ↑ LHTL combined with low-altitude training ↑ LHTL combined with simulated altitude training ↑ LHTH ↑ IHT ↔ IHE ↔ HHL

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Yu et al. [47]	-Overall Population SMD Range: 1.45 (CI = 0.33–2.55) to 7.10 (CI = 2.39–11.74) -Non-Athlete Subgroup IHT vs. LLNT: SMD = 3.02 (CI = 1.63–4.40) RSH vs. LLNT: SMD = 0.54 (CI = 0.03–1.04) -Athlete Subgroup LH TL vs. LL TL: SMD = 0.71 (CI = 0.04–1.39) IHT vs. LL TL: SMD = 0.43 (CI = 0.14–0.73) RSH vs. LL TL: SMD = 0.76 (CI = 0.29–1.23)	NR	NR	Performance (VO ₂ max)	-Overall Population VO ₂ max Gains: ↑ IHT Highest ranking (42%) ↑ SMD range: 1.45 (0.33–2.55) → 7.10 (2.39, 11.74) -Athlete Subgroup VO ₂ max Gains: ↑ IHT: Most effective ↑ IHT, LH TL, LH TH, and RSH: Effective SMD Improvements: ↑ LH TL vs. LL TL: SMD = 0.71 (95% CI [0.04, 1.39]) ↑ IHT vs. LL TL: SMD = 0.43 (95% CI [0.14, 0.73]) ↑ RSH vs. LL TL: SMD = 0.76 (95% CI [0.29, 1.23]) Non-Athlete Subgroup VO ₂ max Gains: ↑ IHT: Most effective (67%) ↑ RTH and RSH: Moderately effective SMD Improvements: ↑ IHT vs. LLNT: SMD = 3.02 (95% CI [1.63, 4.40]) ↑ RSH vs. LLNT: SMD = 0.54 (95% CI [0.03, 1.04])
Westmacott et al. [48]	ΔVO ₂ max HIIT in hypoxia SMD = 1.14 (0.56–1.72) p < 0.001	VO ₂ max HIIT in hypoxia I ² = 67%	NR	Performance (VO ₂ max)	↑ HIIT in hypoxia improved VO ₂ max compared to HIIT in normoxia: (p < 0.001)
Deb et al. [49]	Performance ROM = −17.1% ± 3.7% (−22.8% to −11%), NR	NR	GRADE	Performance and capacity	-Overall Effect of Acute Hypoxic Exposure ↓ Performance: −17.1% ± 3.7% ↓ Altitude effect: −6.5% ± 0.9% per 1000 m elevation ↓ Oxygen saturation (SaO ₂): −2.0% ± 0.4% per 1% reduction -Exercise Type as a Moderator ↓ Time Trials: −16.2% ± 4.3% ↓ Time to Exhaustion: −44.5% ± 6.9% ↔ Intermittent exercise: −5.6% ± 4.8% ↔ Sprint performance: −2.9% ± 8.0% -Exercise Duration as a Moderator ↔ < 2 min: −6.3% ± 5.6% ↓ 2–10 min: −18.0% ± 6.0% ↓ > 10 min: −26.8% ± 5.5%

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Hamlin et al. [50]	-Control Groups: 1 week post-intervention: 20% ± 14%, standardized change = 0.84 (± 0.52) 4 weeks post-intervention: 25% ± 23%, standardized change = 1.04 (± 0.83) -Hypoxic Groups (Intermittent and Live High Combined): -1 week post-intervention: Intermittent Hypoxia: 13% ± 16%, standardized change = 0.57 (± 0.62) Live High Protocol: 13% ± 15%, standardized change = 0.57 (± 0.62) -4 weeks post-intervention: -Intermittent Hypoxia: 19% ± 20%, standardized change = 0.78 (± 0.76) Live High Protocol: 18% ± 19%, standardized change = 0.78 (± 0.74) Comparison Between 1 and 4 Weeks Post-Intervention: -Difference between 4 weeks and 1 week (Intermittent Hypoxia): 5% ± 6%, standardized change = 0.21 (± 0.24)	NR	NR	Performance (high-intensity intermittent running)	Hypoxic Groups: ↑1-week post-intervention: ↑ 13% ± 16% in YYIR performance ↑4 weeks post-intervention: ↑ 19% ± 20% in YYIR performance Live-High Protocols: ↑1-week post-intervention: ↑ 13% ± 15% in YYIR performance ↑4 weeks post-intervention: ↑ 18% ± 19% in YYIR performance Comparison Between Hypoxic Interventions: ↔ (unclear) Impact of Hypoxic Dose: ↔ (unclear)
Précart et al. [51]	-RSA_best SMD = 0.038; 95% CI: -0.252 to 0.328; P = 0.798 -RSA_mean SMD = 0.276; 95% CI: -0.018 to 0.570; P = 0.066 -Sprint decrement score SMD = 0.603; 95% CI: 0.180 to 1.025; P = 0.005 -Max blood lactate SMD = 0.611; 95% CI: 0.223 to 0.999; P = 0.002	RSA_best I ² = 0% RSA_mean I ² = 0% Sprint decrement I ² = 31% Max blood lactate I ² = 0%	NR	RSA_best, RSA_mean, Sprint decrement score, Max blood lactate	↔ RSA_best ↔ RSA_mean ↑Sprint decrement score ↑max blood lactate

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Bonetti et Hopkins [55]	NR	NR	NR	Endurance performance, VO ₂ max	Endurance Performance (Sea-Level Mean Power Output) • LHTL: -Subelite Athletes ↑: 4.2% -Elite Athletes ↑: 4.0% • Artificial Long Continuous LHTL -Subelite Athletes ↔ : 1.4% -Elite Athletes ↔ : 0.6% • Artificial Brief Continuous LHTL -Subelite Athletes ↔ : 0.7% -Elite Athletes ↔ : 0.2% • Artificial Brief Intermittent LHTL -Subelite Athletes ↑: 2.6% -Elite Athletes: n.a • LLTH -Subelite Athletes ↔ : 0.9% -Elite Athletes ↔ : 0.6 VO ₂ max • LHTL -Subelite Athletes ↔ : 6.4% -Elite Athletes ↔ : 6.4% • Artificial Long Continuous LHTL -Subelite Athletes ↔ : − 1.1% -Elite Athletes: n.a • Artificial Brief Continuous LHTL -Subelite Athletes ↔ : 0.1% -Elite Athletes: n.a • Artificial Brief Intermittent LHT -Subelite Athletes ↔ : 1.1% -Elite Athletes: n.a • LLTH↑: 1.1%(possible) -Subelite Athletes ↑: 1.1% -Elite Athletes: ↔ : 0.1%

Table 2 (continued)

Reference	If meta-analyses conducted		Certainty of evidence	Outcome assessed	Main Results
	Effect size (95% CI, p-value*)	I ² (Chi ² , p-value*)			
Yu et al. [53]	n.a	n.a	NR	VO ₂ , VO ₂ max, SpO ₂ , Power Output	VO ₂ • ↔ Beetroot juice and sildenafil • ↔ Ischemic preconditioning VO ₂ max • ↓ Sildenafil • ↔ Beetroot • ↔ IPC SpO ₂ • ↑ Beetroot • ↔ Sildenafil • ↔ IPC Power Output • ↑ Beetroot (in one study, ~ 10% improvement) • ↔ Sildenafil • ↔ IPC
Fentaw et al. [54]	SMD: 0.68 95% CI: [0.30, 1.06] p < 0.001	I ² = 0%	GRADE	VO ₂ max	↑ VO ₂ max after HIIT in hypoxia ↑ VO ₂ max after HIIT in normoxia ↑ Overall effect size (SMD) ↔ Effect of hypoxia type ↔ Effect of training status ↔ Effect of intervention duration ↔ Effect of sex

↑: Indicates an increase, ↓: Indicates a decrease, ↔: Indicates no change, H: hypoxia, N: Normoxia, LLTH: Live Low-Train High, MD: Mean Difference, ROM: Ratio of means, PA: Physical Activity, CABG: Coronary Artery Bypass Grafting, BP: Blood Pressure, HIF: Hypoxia-Inducible Factor, IH: Intermittent Hypoxia, IHE: Intermittent Hypoxia Exposure, IHT: Intermittent Hypoxia Training, IHHE: Intermittent Hypoxia-Hyperoxia Exposure, IHHT: Intermittent Hypoxia-Hyperoxia Training, I-IHT: Long-term high-intensity interval training, CHT: Continuous Hypoxic Training, RSH: Repeated Sprint Training in Hypoxia, ISH: Interval Sprint Training in Hypoxia, s-IHT: term high-intensity Interval training, WMD: Weighted Mean Difference, CI: confidence interval, n.a: not applicable, NR: Not Reported, HR: Heart Rate, VO_{2peak}: Peak Oxygen Consumption, VO₂max: Maximal oxygen uptake, LDL: Low-Density Lipoproteins, Hb: Hemoglobin, NOS: Nitric Oxide Synthase, PEBLC: Peak Exercise Blood Lactate Concentration HRmax: Maximum Heart rate, CSA: Cross Sectional Area, EPO: Erythropoietin, RSA: Repeated Sprint Ability, YYIR: YO-YO Test, PWC: physical work capacity, GRADE: Grading of Recommendations, Assessment, Development, and Evaluations

sessions, may drive the long-term adaptations observed with hypoxic training. Consequently, these findings highlight the importance of tailoring hypoxic dose (duration and severity) and protocols to exercise duration, performance goals, and individual tolerance to hypoxic stress.

Newer evidence adds to these findings: a 2025 MA of 10 RCTs involving 199 trained athletes showed that RSH induced by voluntary hypoventilation at low lung volume (RSH-VHL) led to moderate, significant improvements in sprint-fatigue resistance (SMD = 0.60, *p* = 0.005) and higher peak blood-lactate levels (SMD = 0.61, *p* = 0.002), indicating a stronger glycolytic stimulus [51]. Notably, best and mean sprint outputs remained unchanged. RSH-VHL, which involves controlled breath-holds at the end of expiration, offers a low-cost, field-ready alternative to systemic hypoxia while still eliciting key peripheral adaptations that enhance anaerobic capacity (repeated-sprint performance).

Further evidence on aerobic-specific protocols, such as LHTL, comes is found in a meta-analytic review by Bonetti and Hopkins [55], which assessed the effects of six altitude training strategies on sea-level endurance performance and physiological outcomes. In subelite athletes, natural LHTL and artificial brief intermittent LHTL showed the most consistent benefits (~ 4.2% and ~ 2.6%,

respectively), while LHTH, long continuous LHTL, and LLTH produced trivial or unclear effects. Among elite athletes, performance improvements were more variable, with LHTL offering only a possible benefit (~ 4.0%). When key parameters (altitude level, exposure duration) were optimized, performance gains in subelite athletes reached up to ~ 6.8%, whereas only enhanced LHTL and LHTH protocols showed benefits in elite populations. Notably, VO₂max improvements were observed only with LHTH in subelite athletes, and hematological responses (e.g., hemoglobin mass) were inconsistent and not systematically linked to performance outcomes. To assess protocol effectiveness, the authors used a random-effects MA with sample-size weighting due to limited variance reporting across included studies. Performance and physiological effects were expressed as percentage changes, interpreted using magnitude-based inference with 90% confidence limits. A 1% threshold was used to define the smallest worthwhile change, and p-values were not reported. These findings suggest that LHTL may exert its effects through multifactorial adaptations beyond erythropoiesis or VO₂max alone.

IHHE is a less commonly studied modality, with limited evidence currently available. Behrendt et al. [11] reported that IHHE improved physical work capacity

and autonomic nervous system balance in young track and field athletes with overtraining syndrome. Improvements were reflected by favorable changes in heart rate variability (HRV), including increases in low- and high-frequency power and a more balanced LF/HF ratio. The authors hypothesized that enhanced autonomic recovery and increased antioxidant capacity may have contributed to these effects, although oxidative stress markers were not assessed. However, the absence of a proper control group of overtrained athletes receiving sham IHHE or low-intensity training alone limits the ability to draw firm causal conclusions.

Notably, only two SR with MA have investigated HIIT under hypoxic conditions, both suggesting its potential as a time-efficient and potent strategy to enhance aerobic performance. One MA reported significantly greater $\text{VO}_{2\text{max}}$ improvements under hypoxia compared to normoxia (SMD = 1.14), indicating that the combination of high training intensity and hypoxic stress may elicit synergistic adaptations [49]. These findings are supported by a more recent MA [54], which reported that HIIT performed under hypoxia led to significantly greater improvements in $\text{VO}_{2\text{max}}$ compared to normoxia (SMD = 0.68), with performance gains ranging from 4.4% to 13.6%. Subgroup analyses revealed no significant influence of the type of hypoxia, training status, intervention duration, or sex on the overall effect. Given HIIT's widespread use in athletic and clinical settings [56, 57], its application in hypoxic environments represents a promising yet underexplored area that warrants further investigation.

Regarding muscular strength and hypertrophy, RTH showed favorable effects. Reviews by Gamonales et al. [40] and Benavente et al. [38] reported gains in muscle strength and size, particularly with moderate loads (50–70% 1RM) over 4–8 weeks. However, differences in lean mass and muscle thickness compared to normoxia were often trivial [38]. Recent findings also suggest potential recovery benefits of hypoxic preconditioning. Uzun et al. [35] found that IHHE reduced muscle damage markers and enhanced post-exercise recovery following resistance training.

Hematological responses to hypoxia were mixed. Increases in hemoglobin concentration were observed primarily with prolonged exposures (≥ 14 h/day) [39]. Huang et al. [36] reported increases in Hb (Mean Difference = 0.25, $p = 0.002$) and $\text{VO}_{2\text{max}}$ (MD = 3.20, $p = 0.000$) with LLTH, while Lancaster and Smart [37] observed similar Hb improvements (Weighted MD = 0.57, $p < 0.00001$) and reduced peak lactate concentrations (WMD = - 3.03, $p = 0.0001$). However, the link between hematological changes and performance gains remained inconsistent, particularly in elites.

Finally, an SR on complementary interventions during hypoxic training found that beetroot juice supplementation improved endurance performance and reduced oxygen cost in simulated hypoxia, likely via enhanced oxygen utilization [53]. In contrast, sildenafil and ischemic preconditioning did not show consistent ergogenic benefits.

Overall, IH protocols show strong potential to enhance both aerobic and anaerobic performance, as well as muscular strength and recovery. Among them, LHTL combined with low-altitude training, IHIT, and HIIT under hypoxia emerge as the most effective strategies for improving aerobic capacity. RSH and RSH-VHL are particularly effective for enhancing anaerobic performance, especially repeated-sprint ability and glycolytic adaptations. However, the effectiveness and consistency of these benefits depend on the specific protocol used, exposure parameters, and training or performance status of the subject. Less-studied modalities such as IHHE also show promising early results, but further high-quality research is needed to confirm their efficacy.

Quality Assessment

Methodological Quality Assessment

The methodological quality of the included SRs ranged from low to critically low. Specifically, six SRs were rated as low quality [11, 36, 46, 47, 51, 54], while the remaining three were classified as critically low. Common methodological limitations were observed across most SRs. These included insufficient reporting of funding sources for the primary studies (Item 10) and inadequate consideration of the risk of bias from individual studies when interpreting or discussing results (Item 13). Furthermore, the comprehensiveness of the literature search (Item 4) was generally suboptimal, with most SRs relying on a limited number of databases and omitting searches in trial registers or grey literature sources. One exception was identified, wherein a review was conducted an extensive search across all major databases and grey literature. Nevertheless, all SRs formulated their research questions and eligibility criteria based on PICO components (Item 1), and all but one [35] performed database searches using at least two electronic sources. Disclosure of funding sources and potential conflicts of interest (Item 16) was adequately reported in all but three SRs [35, 37, 43]. For SRs that did not include meta-analyses, items related to meta-analytical methods (Items 11, 12, and 15) were deemed not applicable. Overall inter-rater agreement was strong across all evaluated items, with a Cohen's kappa coefficient of $\kappa = 0.90$. A detailed summary of the methodological quality assessment is provided in Table S2 of the Supplementary Material.

Certainty of Evidence

Among the 22 SRs, only two SRs with MA assessed the certainty of evidence using the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) framework [49, 58].

Overlap of Included Studies

Among the 22 included systematic reviews encompassing 272 primary studies, the corrected covered area (CCA) was 3.1%. After adjusting for publication year, the CCA slightly increased to 3.5%, still indicating a low level of overlap across reviews. This proportion suggests that the included SRs largely relied on distinct sets of primary studies.

Discussion

The present synthesis highlights the multifaceted benefits of IH protocols on physical performance, revealing consistent trends yet notable variability across protocols, outcomes, and populations. Rather than uniformly enhancing performance, the effectiveness of IH training appears to depend on a complex interplay of physiological mechanisms, individual characteristics, and protocol design. These findings invite a deeper exploration of the underlying adaptations that contribute to improved aerobic capacity, anaerobic performance, and muscular strength under hypoxic stress [59–61]. The CCA was 3.5% after adjusting for publication year, indicating a low overall overlap among primary studies and suggesting that the observed effects are unlikely to be substantially influenced by duplicated evidence.

HIIT under hypoxia showed superior $\text{VO}_{2\text{max}}$ improvements compared to normoxic conditions ($p < 0.001$) [48], likely due to a greater reliance on anaerobic metabolism to meet energy demands during training at or above the ventilatory threshold (VT2) [49, 62]. Among the protocols, IHIT was ranked highest for $\text{VO}_{2\text{max}}$ enhancement (SUCRA = 42%); nevertheless, this ranking stems from a single small trial, and further research is needed before drawing firm conclusions [47]. Similarly, RSH has consistently demonstrated improvements in RSA with controlled studies reporting additional performance gains compared to normoxia [41, 63]. These improvements appear to be driven primarily by peripheral vascular and muscular mechanisms, including intensity-dependent microvascular vasodilation mediated by nitric oxide (NO), enhanced oxygen delivery to fast-twitch fibers, and improved phosphocreatine resynthesis between sprints [63–65]. At the molecular level, RSH has been reported to upregulate HIF-1 α and glycolytic transporters such as MCT-1/4, facilitate lactate efflux and pH regulation, while angiogenic signals (e.g., VEGF) support capillarization [63, 66, 67]. These combined adaptations enhance fatigue resistance and sprint maintenance

during repeated high-intensity efforts. Optimal responses are reported with moderate simulated altitudes of ~3000 m, sprint durations of 5–12 s, and exercise-to-rest ratios between 1:2 and 1:6 [63], whereas excessively severe hypoxia (>4000 m) or inadequate training loads may blunt adaptations [68]. While the exact contribution of each mechanism remains to be fully elucidated, the current evidence strongly supports RSH as a potent strategy to enhance repeated-sprint performance through peripheral, intensity-dependent adaptations rather than central hematological changes [63, 69].

Further supporting the efficacy of sprint-based hypoxic modalities, a recent MA on RSH-VHL reported enhanced fatigue resistance, as reflected by a significant improvement in sprint decrement (Sdec) compared to normoxic training. This effect is likely driven by greater glycolytic activation triggered by combined hypoxic and hypercapnic stress [70]. Although no significant effects were observed for RSAbest and RSAm_{mean}, some studies showed individual improvements, especially in the later sprints [51]. The proposed mechanisms include increased lactate production [71], improved pH regulation [72], and a potential “pump effect” enhancing oxygen uptake during recovery [73]. However, protocol variability, limited female representation, and lack of blinding temper the strength of conclusions, highlighting the need for further standardized research.

Additionally, anaerobic training in hypoxia has been shown to reduce perceived exertion (RPE), improving an athlete’s ability to tolerate discomfort and sustain high-intensity efforts for longer durations, ultimately enhancing exercise performance [74].

The hypoxic intensity and exposure duration emerged as critical determinants of performance outcomes. While higher altitudes theoretically provide a stronger adaptive stimulus, evidence suggests the relationship between hypoxic dose and performance benefits may not be linear. For instance, Karayigit et al. [75] found no significant differences in high-intensity intermittent performance between acute moderate and high hypoxia or compared to normoxic conditions. Similarly, a study investigating the effects of sprint interval training at different altitudes (2000 m, 3000 m, and 4000 m) on cycling performance found no significant differences in performance improvements after a six-week training protocol [76]. These findings highlight the complexity of hypoxic adaptations and emphasize the need for individualized training prescriptions, as physiological responses to hypoxia exhibit considerable variability based on participant characteristics and baseline fitness.

Strategies such as LHTL and LLTH are frequently associated with improvements in $\text{VO}_{2\text{max}}$ and, in some cases, with elevated hemoglobin concentrations. However, the validity of these hematological adaptations depends

critically on the total hypoxic dose and requires cautious interpretation. MAs by Gore et al. [77] and Rasmussen et al. [78] indicated significant increases in red cell volume typically occurring only when hypoxic exposure exceeds four weeks at altitudes ≥ 3000 m or involves more than 12 hours per day for several weeks at altitudes above $> \sim 2000$ m [79]. Furthermore, hemoglobin mass appears to increase at a rate of approximately 1% per 100 hours of adequate hypoxic exposure [80], even if it is not always the case. In contrast, the cumulative hypoxic dose in most LLTH—and even some LHTL—strategies often falls short of these thresholds. As such, reported increases in hemoglobin concentration may stem from hemoconcentration (i.e., plasma volume shifts) rather than true erythropoiesis and Hbmass expansion, which can only be accurately assessed using validated methods such as the optimized carbon monoxide rebreathing technique [77]. Therefore, it is more plausible that the performance benefits of LHTL and LLTH are mediated primarily through non-hematological mechanisms such as improved mitochondrial efficiency, capillarization, and ventilatory responses, rather than robust erythropoietic adaptations.

These nuances align with the long-standing debate on the effectiveness of LHTL in elite endurance athletes. Some authors, notably Robach and Lundby, have argued that athletes with already high Hbmass values may approach a physiological ‘ceiling,’ limiting further hematological and performance gains [16, 17, 81]. Indeed, several studies in world-class athletes with near-maximal Hbmass have reported little or no improvement in Hbmass, VO_2max , or performance following LHTL, even under adequate hypoxic exposure [82, 83]. However, this viewpoint has been criticized for relying on studies with potential measurement inaccuracies, where small but meaningful adaptations may have been obscured [19, 20]. In contrast, other authors have shown that when the hypoxic dose is sufficient and Hbmass is measured with precise methods such as optimized CO-rebreathing, both hematological and performance benefits can occur, even in highly trained athletes [18–20]. Recent point-counterpoint discussions suggest that such adaptations in elites are not universal but likely depend on hypoxic dose, training load and regulation, measurement accuracy, and individual responsiveness [84, 85]. More longitudinal, controlled studies in elite athletes are needed to clarify who benefits, under what conditions, and why responses vary so widely.

When key parameters such as hypoxic dose and measurement accuracy are optimized, strategies like LHTL have, in some studies, shown the potential to boost VO_2max [37]. These adaptations are driven by hypoxia-induced erythropoiesis, resulting in elevated hemoglobin levels ($p < 0.00001$) and improved oxygen transport capacity [52, 55, 61]. Additionally, vascular adaptations,

such as increased NO production and enhanced vasodilation, facilitate efficient oxygen delivery to working muscles [36].

Muscular strength and hypertrophy also benefited from RTH [44]. Studies reported significant gains in muscle strength and moderate increases in cross-sectional area under hypoxic conditions [44]. These outcomes are linked to improved glucose transport, glycolytic efficiency, and mitochondrial biogenesis, alongside a regulated inflammatory response and enhanced antioxidant capacity [60]. However, lean mass and muscle thickness showed no consistent differences compared to normoxia, highlighting the specificity of hypoxic adaptations to the training modality and load.

Anaerobic performance improvements depended on the training intensity and protocol, with I-IHT and RSH showing the most significant effects. RSH, in particular, was effective in improving anaerobic performance in sports requiring short, intense efforts. In contrast, continuous low-intensity hypoxic training did not yield significant improvements [46]. RSH was shown to enhance blood flow and muscular adaptations, leading to superior sprinting capabilities compared to normoxic conditions [46]. However, acute hypoxic exposure occasionally resulted in performance decrements for exercise durations exceeding 10 min, likely due to reduced oxidative energy production and limited cardiovascular engagement under hypoxia [46].

The integration of normoxic and hypoxic training sessions has been recommended to mitigate the reduced cardiovascular load during hypoxic sessions, promoting a more balanced development of cardiovascular and muscular systems [21]. McLean et al. [21] emphasized the efficacy of targeted, high-intensity intermittent training methods, such as interval hypoxic training and RSH, in maximizing performance gains.

Despite these promising findings, the variability in individual responses to hypoxia must be acknowledged. Elite athletes, for instance, may experience greater pulmonary limitations under hypoxic conditions, restricting performance benefits compared to less-trained individuals [86]. These differences underscore the importance of tailoring IH protocols to individual characteristics, such as training status, sport-specific demands, and baseline fitness levels, to achieve optimal outcomes.

In summary, the efficacy of IH protocols in enhancing physical performance lies in their ability to stimulate comprehensive physiological adaptations, including improved oxygen transport, muscular efficiency, and energy metabolism. However, optimizing these protocols requires careful consideration of hypoxic dose, training intensity, and individual variability. Future research should focus on refining intervention parameters and

exploring the long-term sustainability of performance benefits in diverse athletic and clinical populations.

Limitations and Future Prospects

Despite the promising effects of IH protocols across various performance domains, several limitations must be acknowledged. First, the methodological quality of the included systematic reviews was predominantly low to critically low, largely due to inadequate risk-of-bias assessments and incomplete literature searches. Notably, the absence of the Risk of Bias in Systematic Reviews (ROBIS) tool represents a methodological shortcoming, as does the limited use of the GRADE framework to assess the certainty of evidence. Although AMSTAR-2 was used to appraise review quality, future umbrella reviews would benefit from integrating ROBIS to enhance the rigor and transparency of their evaluations. Second, significant heterogeneity exists in the terminology used to describe IH protocols. Inconsistent definitions and abbreviations across studies make it difficult to categorize interventions and hinder comparability. A harmonized nomenclature and standardized reporting practices are essential for improving evidence synthesis and translating findings into practice. Similarly, the variability in IH protocol parameters (e.g., duration, intensity, altitude, hypoxic dose) complicates direct comparisons. Establishing clearer guidelines and standardizing intervention designs will be critical for improving reproducibility and optimizing training efficacy. Sex-based differences in IH responses also remain underexplored. Most studies predominantly included male participants, with limited attention to female-specific physiological factors such as menstrual cycle phase, iron metabolism, or menopausal status. These variables may influence adaptation to hypoxia and should be systematically investigated to ensure the generalizability of findings across sexes. Moreover, while hematological adaptations such as increased hemoglobin mass are often discussed, these effects should be interpreted with caution. The total hypoxic dose in many protocols may be insufficient to trigger meaningful erythropoiesis, and overemphasizing this aspect may distract from the more consistently supported non-hematological benefits. The apparent superiority of IHIT for $\text{VO}_{2\text{max}}$ enhancement in NMA results must be interpreted cautiously, as it is based on only one small study ($n=11$). More randomized controlled trials are needed to establish its true efficacy. Finally, while SUCRA values offer useful insights into the probabilistic ranking of interventions in NMA, they should be interpreted with caution. SUCRA scores do not convey absolute effect sizes and are sensitive to the quality and consistency of included studies. Addressing these methodological and population-specific gaps will be essential for accurately evaluating the true performance-enhancing

potential of intermittent hypoxia protocols and for refining their application across different athletic populations and sporting contexts.

Conclusion

IH protocols demonstrate promising potential to enhance multiple domains of physical performance, including aerobic capacity, anaerobic power, muscular strength, and hypertrophy. Among the various strategies, interval-based approaches such as RSH and LHTL appear beneficial, particularly for improving $\text{VO}_{2\text{max}}$ and RSA. IHIT may hold potential, but current evidence is still limited, so no firm conclusions can yet be drawn. These improvements are supported by a range of physiological adaptations, including enhanced oxygen transport, muscular efficiency, and metabolic function. However, hematological changes should be interpreted with caution, as most LLTH and LHTL protocols likely fall short of the hypoxic dose required to induce meaningful erythropoiesis or lasting increases in hemoglobin mass. Notably, more attention should be given to protocols like HIIT under hypoxia and RSH-VHL, which have shown promising efficacy. In particular, RSH-VHL represents a low-cost, field-ready alternative to traditional RSH, expanding the accessibility of hypoxic training. Although IHHE and IHHT have attracted growing interest for their potential benefits, current evidence remains limited, and further investigations are needed to establish their efficacy and clarify their mechanisms of action. Ultimately, outcomes depend on protocol design, exposure characteristics, and individual factors such as training status and hypoxia tolerance. Future research should aim to refine dose-response relationships, personalize interventions, and clarify long-term adaptations. When appropriately prescribed, IH training represents a versatile and effective strategy to optimize performance across diverse athletic populations.

Abbreviations

AMSTAR	Assessing the Methodological Quality of Systematic Reviews
CCA	Corrected Covered Area
IH	Intermittent Hypoxia
IHHE	Intermittent Hypoxia-Hyperoxia Exposure
IHHT	Intermittent Hypoxia-Hyperoxia Training
IHT	Intermittent Hypoxia Exposure
IHT	Intermittent Hypoxia Training
LLTH	Live Low-Train High
RSA	Repeated Sprint Ability
RSH	Repeated Sprint Training in Hypoxia
SIH	Sprint interval Training in Hypoxia
RTH	Resistance Training in Hypoxia
RSH-VHL	Repeated-Sprint training in Hypoxia induced by Voluntary Hypoventilation at Low lung volume
HIIT	High-Intensity Interval Training
CHT	Continuous Hypoxic Training
ROBIS	Risk of Bias in Systematic Reviews
ROS	Reactive Oxygen Species
OSA	Obstructive Sleep Apnea
SM	Supplementary Material

SR	Systematic Review
MA	Meta-analyses
NMA	Network meta-analyses
VO ₂ max	Maximal oxygen consumption
Hb	Hemoglobin
FiO ₂	Fraction of Inspired Oxygen
EPO	Erythropoietin
HIF	Hypoxia-Inducible Factor
VEGF	Vascular Endothelial Growth Factor
NO	Nitric Oxide
HR	Heart Rate
IHIT	Intermittent Hypoxic Interval Training
RCT	Randomized Controlled Trial
NRIS	Non-Randomized Interventional Study
SUCRA	Surface Under the Cumulative Ranking
GRADE	Grading of Recommendations, Assessment, Development, and Evaluations
MeSH	Medical Subject Headings
PRIOR	Preferred Reporting Items for Overviews of Reviews

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

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Author contributions

AB, AP, and OD conceived the idea for this review. AB conducted the literature search. AB, OD, and AP were responsible for selecting the articles to be included in the review. AB and AP extracted data. AB and NLB assessed the methodological quality. NLB conducted the overlap analysis. AB wrote the first draft of the manuscript. OD, AP, and NLB provided revisions to the original manuscript. All authors read and approved the final version.

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Data availability

This umbrella review is based on secondary data extracted from previously published systematic reviews and meta-analyses. For access to the supplementary material, see 'Supplementary Information'.

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Competing interests

The authors declare no conflicts of interest.

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