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Systematic Review

Exploring the Potential Benefits of Interventions When Addressing Simulated Altitude Hypoxia during Male Cyclist Sports: A Systematic Review

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Featured Application: This article explores the potential benefits of intervention with acute hypoxia cycling training protocols on player sports performances, including different interventions and supplementations.

Abstract: Training in hypoxic environments enhances endurance, but the various influences of training protocols and supplementation for efficient performance are not yet clear. This systematic review explored the effects of different supplementations and interventions used to optimize the aerobic and anaerobic performance of cyclists. Data were collected from the following sources: PubMed, Google Scholar, EMBASE, WOS, Cochrane Central Register of Controlled Trials, and randomized controlled trials (RCTs). Studies that explored the effects of supplementation or intervention during cycling were selected for analysis. Five studies (67 male cyclists; mean age, 23.74–33.56 years) reported different outcomes from supplementation or intervention during the acute hypoxia of cyclists. Three studies (42 male cyclists; mean age, 25.88–36.22 years) listed the benefits of beetroot juice in preserving SpO_2 (pulse oxygen saturation) and enhancing high-intensity endurance performance, effectively preventing the reduction in power output. This systematic review provided evidence that the different effects of ischemic preconditioning (IPC), sildenafil, and beetroot (BR) supplementation and intervention did not present a statistically greater benefit than for normoxia groups, but BR supplementation promoted the benefits of SpO_2. Future research should evaluate the duration and higher FiO_2 (simulated altitude, hypoxia) levels of hypoxia in training protocols for cyclists. This is important when determining the effectiveness of supplements or interventions in hypoxic conditions and their impact on sports performance, particularly in terms of power output.

Keywords: altitude; cyclist; supplementation; beetroot; sildenafil; ischemic preconditioning

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1. Introduction

As industry advances, the possibilities of using hypoxic conditions in the training of athletes have increased. Hypoxic training, also known as plateau training, has become a common method to improve sports and exercise performance [1,2]. Hypoxia occurs when body tissues are deprived of sufficient oxygen [3,4], and this concept is used in training to enhance athletic performance by exploiting the physiological effects that maximize athletic performance capabilities, increase cardiorespiratory endurance and power output, and induce specific physiological adaptations [5]. Diverse protocols in hypoxia training can be adapted to suit the specific physiological demands of various sports [5]. Compelling evidence from meta-analysis research has demonstrated that exposure to hypoxia in high-intensity interval training (HIIT) results in greater productivity than nomoxia [6].

As hypoxia training can improve the benefits of aerobic and anaerobic performance [5], cyclists can use these improvements to obtain greater achievements by incorporating hypoxia training protocols and supplementation into their routines. Events held in Europe often take place at moderate elevations, ranging from 1500 to 2999 m above sea level. These altitudes are not extreme enough to cause sickness but affect athletes by impairing endurance due to a lower oxygen availability for muscles [7].

Competitive cyclists frequently face the physiological challenges posed by this reduction in oxygen concentration. They encounter long distances and a variety of elevations, which makes this type of training particularly advantageous. As professional cyclists have a higher VO_2 max [8], functional threshold power [9], and power output, these functions can also be used to predict performance [10,11]. Therefore, simulated high-altitude training at sea level is considered to be an effective training method [2,5,12].

Supplementation with dietary nitrate (NO_3) has been found to improve the physiological effects on blood flow and the body's oxygen consumption, thus avoiding deficits when performing at altitude [13,14]. Beetroot, a natural edible vegetable, contains nitrates; these can improving the performance of athletes in hypoxic environment conditions [13]. A meta-analysis conducted by Silva et al. included 123 studies and indicated that improving exercise performance with nitrate via beetroot juice was the optimal method [8]. The supplement sildenafil has also been demonstrated to enhance cardiorespiratory performance [15] by reducing hypoxic pulmonary vasoconstriction (HPV), thus improving exercise performance. The HPV response redirects blood from less-ventilated lung areas with low oxygen levels to areas with better ventilation, thus improving arterial oxygen levels [16]. Not only has supplementation demonstrated beneficial effects in hypoxic conditions, but the intervention of ischemic preconditioning (IPC) has also been found to enhance tissue tolerance against O_2 deprivation and has been demonstrated to increase local blood flow and O_2 delivery [17–20].

Not all supplementations and interventions have positive effects in insufficient oxygen conditions. Research into supplementation with dietary nitrate (NO_3) observed benefits in a group of women but not in well-trained endurance athletes [21]. Specifically, certain studies have revealed that beetroot supplementation does not enhance the performance of cyclists [22–26].

Previous system reviews have compared training protocols [6] as well as the effects of supplementation on various participants [8,21] and muscle strength [27]. However, there is no systematic review examining the effects of supplementations or interventions on cyclists training under hypoxic conditions. Hence, we conducted a systematic review to determine the effectiveness of supplementations or interventions on the performance of cyclists during hypoxia training in a simulated environment.

It is important to recognize that not every training protocol designed for hypoxic conditions leads to performance improvements for cyclists, just as not every supplement or intervention may prove to be beneficial. The purpose of the present study was twofold: (1) This study aimed to determine whether the use of beetroot, sildenafil, and IPC during hypoxic cyclist training enhances cardiorespiratory capacity and performance in aerobic and anaerobic environments. (2) This systematic review provides practical applications of findings on the physiological effects of hypoxia training programs for athletes and coaches, particularly with regard to supplementation and intervention.

2. Materials and Methods

2.1. Design

This systematic review adhered to the PRISMA guidelines [28] (Figure 1), ensuring a thorough and transparent synthesis of the existing literature for a systematic and unbiased analysis.

The review was pre-registered in the PROSPERO registry (CRD NO. 42024527165), and inclusion criteria were defined following the PICOS guidelines proposed by Brown et al. [29] (Table 1). We perform an in-depth qualitative critical review in the discussion.

Table 1. The meta-analysis was conducted using the PICOS model.

Parameter	Inclusion Criteria
Population	Cycling, Time Trial
Intervention	Hypoxia, Simulated Altitude
Comparators	Treatment or Placebo and Control Group
Outcome	VO_{2peak}, VO_2max, SpO_2, POP
Study Design	Randomized Controlled Trials

SpO_2, pulse oxygen saturation; POP, power output figures, tables, and schemes.

2.2. Inclusion Criteria

This systematic review included studies that met the following criteria: (1) those that examined the immediate effects of acute hypoxic conditions on cyclists with various interventions and supplementations; (2) those with an experimental or quasi-experimental design; and (3) those providing information on pre- and post-treatment assessments (e.g., one-repetition values for VO_2, VO_2max, SpO_2, and power output).

The studies were excluded if they: (1) lacked full-text availability; (2) did not specify the measurement protocols and key methodological aspects of hypoxic conditions; (2) used vascular occlusion methods; (3) involved minors or individuals with pathologies; (4) investigated hypoxia interventions and supplementations in natural conditions (e.g., altitude training); (5) examined interventions and supplementation methods other than hypoxia; and (6) explored the acute effects of interventions and supplementation.

2.3. Sample

The study spanned from November 2013 to November 2023. We used online databases, including PubMed, Google Scholar, Excerpta Medica Database (EMBASE), and Web of Science (WOS). We examined the reference lists from the selected studies to identify any additional relevant articles. The literature search was conducted using a combination of free text and thesaurus terms, incorporating keywords such as (hypoxia OR altitude OR time trial OR simulated altitude) AND (intervention OR beetroot OR sildenafil OR Ischemic Preconditioning OR cyclist OR cycling OR time trial). Additionally, the reference lists of the included studies were scrutinized to identify further eligible articles.

Three independent reviewers K.-C.W, and C.-Y.C, conducted the literature search and resolved inconsistencies through a consensus. Titles and abstracts were reviewed to first determine their relevance, and those lacking sufficient information underwent further evaluation from a full-text examination. Relevant full-text articles were then screened for potential inclusion in the systematic review based on the pre-defined criteria.

2.4. PICOS Model

This study adhered to the Population, Intervention, Comparator, Outcome, and Study Design (PICOS) framework, as outlined in Table 1.

PRISMA Flowchart

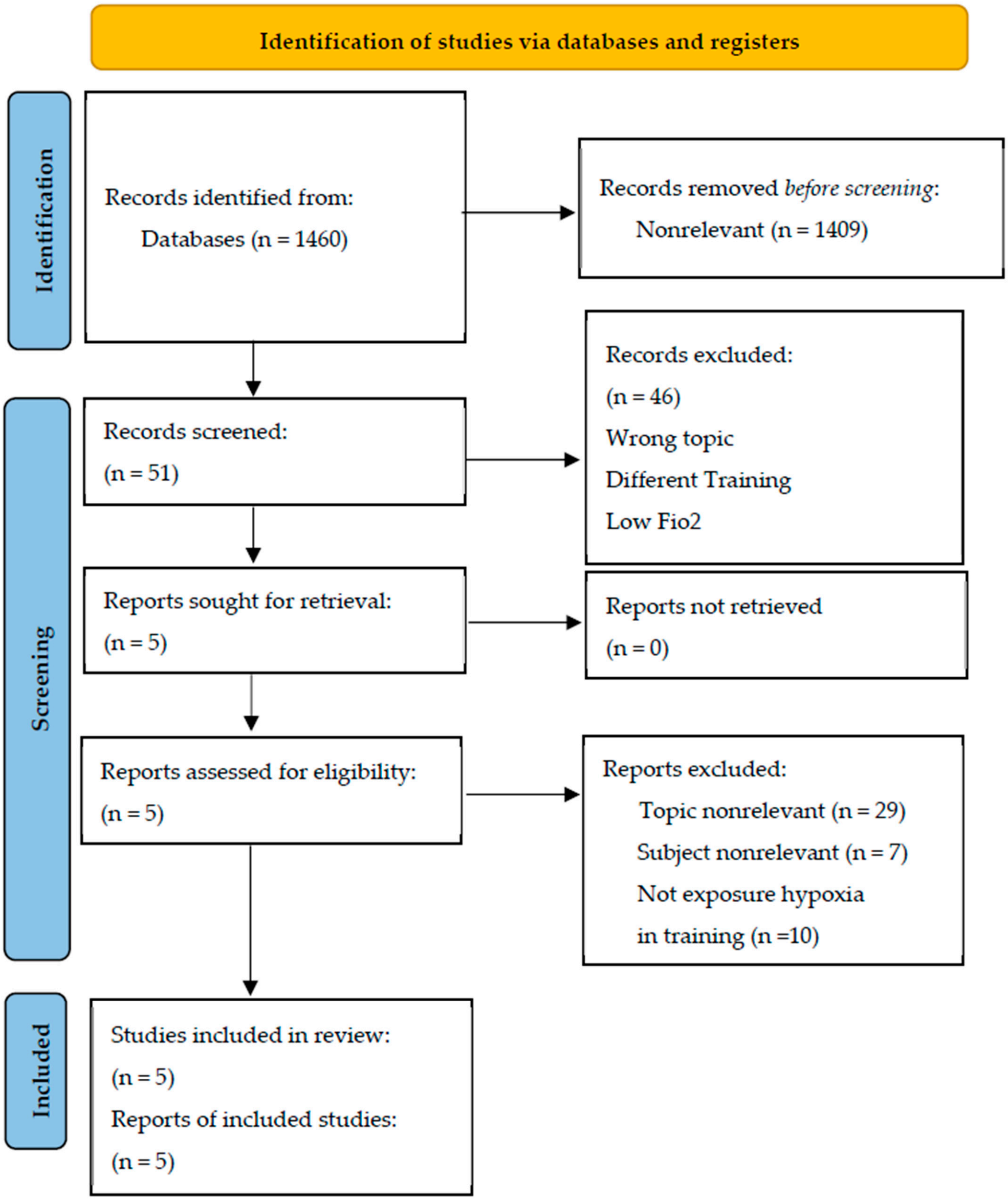

Figure 1. PRISMA flowchart for study selection.

3. Results

The database search returned 1460 studies (Figure 1). After screening the titles and abstracts and excluding non-relevant articles, 51 full-text articles were assessed. Among these, 46 were excluded as they did not meet the eligibility criteria. Ultimately, five articles met the inclusion criteria and were included in the quantitative analysis.

The five randomized controlled trials spanned from 2014 to 2019 [14,22,23,30,31]. One study employed single-blinding for participants [30], whereas four studies used double-blinding [14,22,23,31]. The analysis involved male cyclists who experienced acute hypoxia during cyclist sports and who were aged between 20 and 46 years (mean age 23.74 to 33.56 years) [14,22,23,30,31]. Table 2 provides a summary of the included studies.

In this systematic review, the statistical results from the studies were selectively extracted for the purposes of data analysis and validation. This selective approach was dictated by the limited corpus of the available research, which comprised fewer than ten studies. We have included the statistics result of forest plots in the Supplementary Materials to facilitate further research on the topic.

3.1. Effects of Intervention and Supplementation

Cyclists can enhance their performance in hypoxia and hypobaric hypoxia settings using methods such as beverage supplementation, beetroot juice, intervention ischemic preconditioning, and sildenafil administration [14,22,23,30,31]. The study of Muggeridge et al. [14] indicated an immediate performance improvement with a single intervention of beetroot juice despite the training environment and frequency variations.

3.1.1. Supplementation of Beetroot Juice and Sildenafil and Interventions of Ischemic Preconditioning on VO_2

The use of beetroot juice and sildenafil as interventions in the context of VO_2 outcomes was investigated in studies [14,22,23,31]. Only two articles provided specific data within the research content despite multiple trials being reported across all studies with pre- and post-intervention data. Owing to limited data availability, the analysis exclusively focused on the data collected after the beetroot juice and sildenafil trials as well as before and after the interventions [22,31].

3.1.2. Supplementation of Beetroot Juice and Sildenafil and Interventions of Ischemic Preconditioning on VO_2max

The studies examined the use of beetroot juice and sildenafil as interventions on VO_2max outcomes [23,31]. Despite the inclusion of multiple trials along with pre- and post-intervention data from various studies, only two articles presented specific data within the research content. A discernible influence on cardiovascular function or exercise performance was lacking. Due to limited data availability, the analysis exclusively focused on the information collected after the beetroot juice and sildenafil trials as well as before and after the VO_2 max interventions. The statistical results of the maximal oxygen consumption (VO_2 max) before and after the supplementation with sildenafil did not reach a significant difference. Nevertheless, the mean value decreased by 15.28, with a standard deviation of decrease of $\pm$1.31. This indicated a slight difference the intervention of sildenafil on the VO_2 max [22,31].

3.1.3. Supplementation of Beetroot Juice and Sildenafil and Interventions of Ischemic Preconditioning on SpO_2

The effects of beetroot juice and sildenafil on SpO_2 were then analyzed. Additional supplements included beetroot juice and sildenafil, with researchers delving into the effects of these interventions [22,23,31]. Sildenafil was administered 30 min prior to the initiation of a time trial, following a standardized protocol involving a 15 min exercise program at 60% peak power output and a subsequent 16.1 km time trial. An integrated analysis of these studies along with research on beetroot juice supplementation emphasized the immediate and effective strategy provided by beetroot juice in preserving SpO_2 and enhancing high-intensity endurance performance, especially at moderate elevations. The findings from two studies on beetroot juice support the observation that the decrease in SpO_2 values was less than that of sildenafil [22,23].

3.1.4. Supplementation of Beetroot Juice and Sildenafil and Interventions of Ischemic Preconditioning on Power Output

We examined the effects of intervention and supplementation on power output as addressed by three distinct studies conducted by different research teams using both experimental and control groups [23,30,31]. In general, the supplementations and interventions did not reveal a significant increase in power output. However, a thorough analysis of Puype et al.'s study data before and after their intervention highlighted that beetroot supplementation effectively alleviated an increase in power output [23]. The power output values also exhibited a difference, with an enhancement in the power output of approximately 10%.

3.2. Study Characteristics

The summary of the included studies provides in Table 2 the characteristics including, the Fio2, study design, adjunctive/intervention, duration, and outcome results.

Table 2. Study characteristics in benefits of interventions.

Author, Year	Simulated Altitude; Hypoxia (FiO_2)	Participant Exp and Con of Study Design (Group)	Supplementation/ Intervention	Therapy Intervention Duration	Outcome Measured
Muggeridge et al., 2014 [14]	NH: 15% ~2500 m	Exp:9, Con:9	BR	4 times, 16.1 km, TT	VO_2, SpO_2
MacLeod et al., 2015 [22]	NR: ~2500 m HY: ~2500 m	Exp:11, Con:11	BR	1 time, 10 km, TT	VO_2, SpO_2
Puype et al., 2015 [23]	NH: 12.5% ~4000 m	Exp:22, Con:22	BR (nitric acid)	1 time/30 min, TT, 6 weeks	VO_2max, SpO_2
Paradis-Deschênes et al., 2018 [30]	Low: 18% ~1200 m Mod: 15.4% ~2400 m	Exp:13, Con:13	IPC	4/times, 5 km, TT	SpO_2, POP
Carter et al., 2019 [31]	NOR: 20.9% HYP: 14.7% ~3000 m	EXP:12, Con:12	Sildenafil	1 time, 16.1 km, TT, week	VO_2, VO_2max, SpO_2, POP

NH: Normobaric hypoxic; BR: beetroot; VO_2: peak oxygen consumption; SpO_2: pulse oxygen saturation; NR: normoxia; HY: hypoxia; VO_2max, maximum oxygen consumption; IPC: ischemic preconditioning; NOR: normal; HYP: hypoxia; TT: time trial; POP: power output.

3.3. Risk of Bias

Figure 2 presents the assessment of each study included. No publication bias was detected.

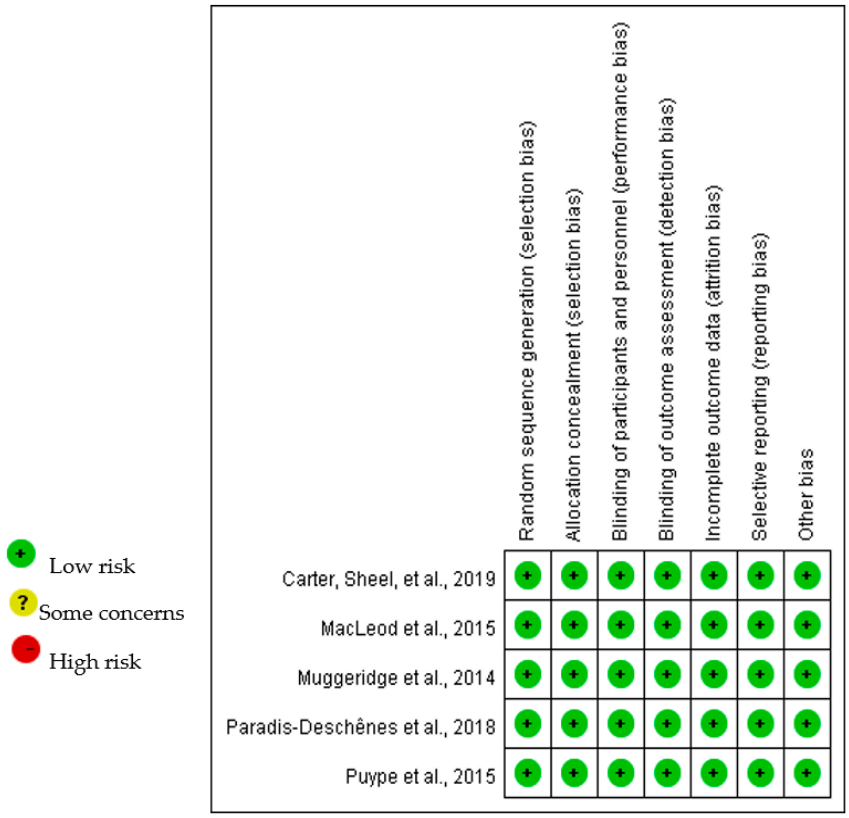

Figure 2. Risk of bias evaluated using a color-coded system [14,22,23,30,31] (green = low risk; yellow = unclear risk; red = high risk).

4. Discussion

4.1. Main Study Findings

This systematic review aimed to critically assess the efficacy of supplemental sildenafil and BR administration as well as the intervention of IPC in influencing physiological effects during hypoxia training in cycling. Regarding aerobic ability, neither beetroot juice nor sildenafil supplementations had an impact on the VO_2 outcomes, including the VO_2 max and SpO_2 levels. Regarding anaerobic ability, neither beetroot juice nor sildenafil demonstrated a significant increase in power output. Only a supplementation of beetroot juice improved high-intensity endurance performance in the condition of hypoxia at a moderate altitude. We investigated the physiological effects of supplementation and intervention in hypoxic conditions and explored the potential of hypoxia training protocols to enhance the performance of cyclists.

4.2. Explanations for the Study Findings

4.2.1. How Does Hypoxic Training Improve Performance?

Regarding the impact of exposure to hypoxia on exercise performance, studies have demonstrated that systematically reducing hypoxic concentration during training can induce various physiological and structural changes in skeletal muscle that are increasing due to the oxidative process [32,33]. This, in turn, can enhance exercise performance. Research has demonstrated that high-intensity interval training in a low-oxygen environment can provide benefits for cardiorespiratory fitness. These benefits include improvements in oxygen uptake (VE), oxygen consumption (VO_2), heart rate (HR), oxygen saturation (SpO_2), blood lactate, heart rate variability (HR), and blood glucose. The article discusses HR variability, hemodynamic function (specifically stroke volume and heart rate [12,34,35]), and hemodynamic variables (including erythropoietin, EPO, hypoxia-inducible factor and blood lactate [12,34,35]). Hemodynamic variables, including erythropoietin (EPO), hypoxia-inducible factor 1 (HIF1), nitric oxide levels, endothelial l growth, transforming growth factor (TGF-β), and inflammatory response-related cytokine TNF-α, as well as neutrophils and bicarbonate (HCO23), have been found to play a role in significant muscle perfusion. This may lead to delayed fatigue during sprinting, and major motor groups may make better use of fast-twitch fibers. Faiss et al. [36] suggest that this delay in fatigue may be due to the use of less anaerobic energy through fast-twitch fibers (Faiss, Léger, Vesin, Fournier, Eggel, Dériaz, and Millet [36]). Prolonged exposure to severe ambient hypoxia reduces the mitochondrial content of muscle fibers. As a result, muscle oxidative metabolism shifts to a greater reliance on carbohydrates for fuel, and intracellular lipid substrate storage decreases. Hypoxia-inducible factor 1 (HIF-1) is a master regulator of gene expression involved in the response to hypoxia [37].

4.2.2. Dietary Nitrate and IPC Effects of Oxygenation Status

The increase in NO in the body has been observed to regulate many important physiological functions, including neurotransmission, immunity, and blood-flow regulation, as well as cause alterations in the body's oxygen consumption [13]. Research has demonstrated that the nitrate content in beetroot is a crucial precursor for the synthesis of nitric oxide (NO) in the body [13]. Elevated levels of blood NO can have positive effects on health and sports performance. The effects include enhanced cognitive functions, improved exercise performance, better cardiovascular responses, and the delayed onset of fatigue [38–40].

Our systematic review of male cyclists experiencing hypoxic conditions and considering supplementation observed no effects on time-trial performances. The reasons for the lack of significant findings may be because adaptations such as increased nitric oxide (NO) production in response to shear stress have been noted in trained endurance cyclists along with a higher VO_2 peak [41,42]. A 4-week cycling training regimen decreased nitrate (NO^-) and nitrite ($NO_2{}^-$) consumption by the human forearm, suggesting an upregulated NO synthesis via the NOS pathway [43]. Supplementation with beetroot juice and sildenafil during moderate hypoxia was observed to enhance arterial oxygen transport, but also reduced muscle metabolic disturbance during exercise with submaximal intensity and hypoxia [44]. Enhancing the nitrate–nitrite–NO pathway can restore exercise tolerance and muscle function to normal levels in low oxygen, showing potential for significant therapeutic benefits. Nitrate supplementation leads to more efficient oxygen use and lower blood lactate during exercise in hypoxia. [45]. In the time trial performance, it was observed that dietary nitrate NO_3 supplementation was less effective [46]. Considering the specific focus on time trial training protocols among cyclists in the studies, with only one employing HIIT protocols [23] under hypoxic conditions, beetroot supplementation may only impact oxygen saturation levels (SpO_2) during extreme altitude hypoxemia (FiO_2 = 11%) [45].

In the other supplementation of sildenafil, a study revealed that sildenafil increased the maximum workload and cardiac output at normoxia but did not affect oxygen saturation in the arteries at high altitudes, either when at rest or during exercise [15]. Additionally, this supplementation has also demonstrated effectiveness in enhancing oxygen delivery [47]. A nitric oxide (NO) supplementation had minor effects on trained athletes [48] and was also less effective when considering the workload of a time trial [46]. It is readily discernible why NO supplementation does not confer any physiological advantages on cyclists or enhance their performance.

In the IPC intervention, as per studies, it enhances peripheral muscles' oxygen utilization but seems ineffective in improving VO_2 max [49,50]. Additionally, IPC's impact on cardiovascular hemodynamics and SpO_2 is negligible, whether at rest, during moderate exercise, or at peak workload in hypoxic conditions [51]. It is suggested that IPC's influence on pulmonary artery systolic pressure (PASP) is not substantial enough to affect cardiovascular outcomes or SpO_2 significantly [52]. Despite the potential benefits of IPC, it has minimal effect on overall oxygen transport during rest or physical activity under acute hypoxia.

4.3. Exploration of Training Protocols Using Supplementation in Hypoxia Training for Endurance Cyclists

4.3.1. Time of Exposure to Hypoxia and EPO Production

The production of erythropoietin (EPO) is elevated during hypoxic conditions, which raises the number of red blood cells. This augmentation enhances the delivery of oxygen to tissues that are experiencing ischemic stress [53]. An increase in EPO levels requires time under hypoxic conditions. During intermittent exposure to hypoxic conditions, a series of eight sequences of 32 min and 120 min of continuous hypoxia was observed to significantly raise the serum erythropoietin concentrations in healthy individuals with peak levels of EPO observed 4.5 h after exposure [54]. In our review, we found that no study design lasted longer than two hours or provided sufficient time for intermittent hypoxic exposure. Although hypoxia can induce hypoxia-inducible factor (HIF-1) alpha, without enough time to stimulate erythropoietin (EPO) production, the capacity to improve aerobic performance during aerobic activity may not be realized.

Levine and Stray-Gundersen [55] stated that exposure to hypoxia enhances the erythropoietin response, leading to an increase in the erythrocyte volume and efficiency of oxygen transport. Knaupp et al. [56] conducted a study on the relationship between exposure duration in hypoxia and plasma levels of erythropoietin (EPO) in a generally healthy population. No increase in erythropoietin was observed after 5 min and 60 min exposures at an oxygen concentration of 11.05%. However, a 50% increase in EPO was cumulatively observed after 120 min of exposure to hypoxic exposure. A 52% increase in EPO was observed after a 360 min exposure to hypoxia. Our study concluded that exposing the general population to a 120 min oxygen concentration of 11% did not result in an increase in erythropoietin levels. This method is not recommended when reducing the EPO levels of the general population. Exposing the average healthy person to hypoxic conditions with an oxygen concentration of 11.05% continuously for 120 min or intermittently for 240 min can stimulate the production of EPO.

4.3.2. The Effects of FiO_2 and Red Blood Cells

EPO can lead to an increase in red blood cell production [53]. The red blood cell volume response to hypoxia is typically a gradual process [57]. Exposure exceeding two weeks at altitudes above 4000 m is necessary for a significant effect. Longer periods are required at altitudes below 3000 m, with no increase observed within four weeks [57]. When considering the effects of the altitude of FiO_2, Berglund's research revealed that the EPO increased by 30% after 2~3 days at a moderate altitude; at a high altitude of 4500 m, the EPO increased by 300% and the red blood cells increased by 1% after 7 days at a moderate altitude [58]. When exposed to a hypoxia condition, the EPO of endurance-trained athletes increased after 3 h, even if they had trained using submaximal protocols or were resting at this altitude [59].

4.3.3. Training Protocols Used in Hypoxic Conditions to Improve Performance

Regarding the impact of exposure to hypoxic conditions on exercise performance, studies have demonstrated that systematically reducing the hypoxic concentration during training can induce various physiological and structural changes in skeletal muscles that increase the oxidative process [32,33]. This can enhance exercise performance. Research has demonstrated that high-intensity interval training in a low-oxygen environment can provide benefits for cardiorespiratory fitness. These benefits include improvements in oxygen uptake (VE), oxygen consumption (VO_2), heart rate (HR), oxygen saturation (SpO_2), blood lactate, heart-rate variability (HRV), and blood glucose. Studies have discussed HR variability, hemodynamic functions (specifically stroke volume and heart rate) [12,34,35], and hemodynamic variables (including erythropoietin, EPO, hypoxia-inducible factor, and blood lactate) [12,34,35]. Hemodynamic variables, including EPO, hypoxia-inducible factor 1 (HIF-1), nitric oxide levels, endothelial l growth, transforming growth factor (TGF-β), and inflammatory response-related cytokine TNF-α, as well as neutrophils and bicarbonate (HCO23), have been observed to play a role in significant muscle perfusion. This may lead to delayed fatigue during sprinting. Major motor groups may make better use of fast-twitch fibers. Faiss et al. [36] suggested that this delay in fatigue may be due to the use of less anaerobic energy through fast-twitch fibers [36]. Prolonged exposure to severe ambient hypoxia reduces the mitochondrial content of muscle fibers. As a result, muscle oxidative metabolism shifts to a greater reliance on carbohydrates for fuel, and intracellular lipid substrate storage decreases. Hypoxia-inducible factor 1 (HIF-1) is a master regulator of the gene expression involved in the response to hypoxia [37].

Short-term dietary nitrate supplementation has been established as a method to enhance oxygenation within arterial and muscle tissues, yet it does not appear to influence cerebral oxygenation amidst strenuous hypoxic exercise. Such an enhancement may be more pronounced or improved at higher simulated altitudes or under conditions of more extreme oxygen concentrations where trained athletes seek performance gains. The hormone EPO has been documented to cause an increase in red blood cell production, which is a response that usually gradually unfolds [53]. An exposure of over two weeks at altitudes above 4000 m is required to observe a significant effect from this response. If exposure to severe ambient hypoxia is prolonged, it can lead to a decrease in the mitochondrial content in muscle fibers. This causes a shift in the muscle oxidative metabolism towards a greater dependence on carbohydrates for energy, concurrently reducing the storage of intracellular lipid substrates.

4.4. Strengths and Limitations

This inaugural systematic review explores the impact of training in a hypoxic environment on cyclists. The findings underscore the importance of formulating comprehensive plans and research strategies, encompassing diverse interventions and supplement protocols. Future studies are encouraged to expand the scope of interventions and supplements and consider different time periods for implementation. This framework establishes a fundamental understanding of hypoxic training in cyclists, aiming to enhance their cardiorespiratory and power performance. Limitations include a concentrated focus on hypoxic supplements and interventions, the limited exploration of intervention methods and supplements, and a potential influence on overall effectiveness due to statistical heterogeneity.

5. Conclusions

Our systematic review demonstrates that although IPC and sildenafil may not uniformly demonstrate desired enhancements in acute simulated altitude hypoxia conditions, the nuanced effects of BR and NO_3 supplementation underscore the complexity of optimizing endurance performance at various altitudes. Only supplementation involving beetroot has been evidenced to enhance SpO_2. Future research should assess the duration of exposure before training sessions and consider the established training protocols for cyclists when evaluating the efficacy of supplements or interventions under hypoxic conditions. It is crucial to assess the effectiveness of supplements or interventions on the sports performance of athletes when considering the effects of training in hypoxic conditions. The potential impact on power output should be considered as a means to enhance performance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14073091/s1.

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