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The impact of beetroot juice supplementation on performance in endurance sports: A review of running, cycling, and swimming

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Abstract

Background. Dietary nitrate (NO_3^-) supplementation, primarily via beetroot juice (BRJ), has emerged as a premier ergogenic strategy in contemporary sports science. The physiological mechanism is centered on the nitrate–nitrite–nitric oxide (NO_3^-, NO_2^-, NO) pathway, which increases nitric oxide bioavailability, particularly under conditions of low oxygen tension and metabolic acidosis.

Aim. This review aims to critically evaluate the effects of BRJ on physical performance and physiological markers in long-distance running, cycling, and swimming, based on evidence from 2020–2025, and to establish standardized supplementation protocols for endurance athletes.

Material and methods. A systematic search of PubMed, Scopus, and Web of Science was conducted to identify high-quality meta-analyses, umbrella reviews, and randomized controlled trials (RCTs). Inclusion criteria focused on studies evaluating exercise economy (VO_2), time-trial performance, and recovery markers in both recreational and elite cohorts.

Results. Current evidence indicates that BRJ significantly reduces the oxygen cost of submaximal exercise by 1.5–5.0%. In recreationally active individuals, BRJ increases time-to-exhaustion (TTE) by approximately 15.7% ($p < 0.005$). In cycling, improvements in power output range from 1.2% to 3.0%, while running economy is enhanced via optimized recruitment of Type II muscle fibers. Swimming-specific data highlight improved stroke efficiency and accelerated post-exercise lactate clearance. Chronic supplementation (3–7 days) is identified as the most effective strategy for elite athletes to bypass the "ceiling effect" associated with high baseline nitric oxide levels.

Conclusions. Beetroot juice is a scientifically validated, safe, and effective natural ergogenic aid. Optimal results are consistently achieved through a chronic protocol involving >8 mmol of NO_3^- per day, with specific attention to the timing of ingestion and maintenance of the oral microbiome.

Key words: Beetroot juice; Nitrates; Endurance performance; Running; Cycling; Swimming; Nitric Oxide.

Introduction

In the contemporary landscape of sports science, the pursuit of marginal gains has led to the intensive investigation of nutritional interventions capable of enhancing metabolic efficiency and delaying the onset of neuromuscular fatigue. Among these, dietary nitrates (NO_3^-) have emerged as one of the most robust, evidence-based strategies for endurance athletes. Beetroot juice (BRJ) serves as a primary, concentrated natural source of these inorganic nitrates, offering a unique physiological advantage through the nitrate-nitrite-nitric oxide (NO_3^-, NO_2^-, NO) pathway [4, 8, 12]. Beyond its nitrate content, beetroot is a complex "superfood" containing a dense profile of bioactive compounds, including betalains (betacyanins and betaxanthins), polyphenols, and various antioxidants, which collectively contribute to its anti-inflammatory and vascular-protective properties [1, 18].

1.1. The Enterosalivary Circulation and Biochemical Cascade

The fundamental mechanism behind BRJ's efficacy lies in its ability to increase the systemic bioavailability of nitric oxide (NO), a potent gaseous signaling molecule. Unlike the classical, oxygen-dependent L-arginine-nitric oxide synthase (NOS) pathway, the nitrate reduction process is an exogenous alternative that remains highly active under conditions of low oxygen tension and metabolic acidosis—physiological environments characteristic of high-intensity endurance exercise.

Upon ingestion, dietary nitrates are rapidly absorbed in the upper gastrointestinal tract, leading to a significant increase in plasma nitrate concentration. Approximately 25% of this circulating nitrate is actively taken up by the salivary glands and concentrated in the saliva. This "enterosalivary circulation" is a critical stage where commensal anaerobic bacteria located on the dorsal surface of the tongue (primarily species such as *Veillonella* and *Staphylococcus*) reduce NO_3^- to nitrite (NO_2^-) [4, 15]. Once swallowed, these nitrites are further reduced to bioactive NO in the acidic environment of the stomach or through various deoxygenated heme proteins (such as deoxyhemoglobin and myoglobin) and enzymes (such as xanthine oxidoreductase) in the blood and peripheral tissues [13, 21].

1.2. Cellular and Molecular Mechanisms of Ergogenic Action

Nitric oxide exerts multi-faceted ergogenic effects that target the very foundation of endurance capacity. At the vascular level, NO induces systemic vasodilation by stimulating guanylyl cyclase in vascular smooth muscle, which increases skeletal muscle blood flow and oxygen delivery [4]. Crucially, recent evidence suggests that this increased perfusion is directed preferentially toward Type II (fast-twitch) muscle fibers, which often exhibit lower oxygenation and are more prone to fatigue during intense efforts [6, 11].

At the cellular level, NO optimizes mitochondrial function by modulating the efficiency of oxidative phosphorylation. It has been shown to reduce the "leakage" of protons across the inner mitochondrial membrane, thereby improving the P/O ratio (the amount of ATP produced per oxygen molecule consumed) [13]. Furthermore, BRJ supplementation appears to enhance muscle contractile function by improving calcium (Ca^{2+}) handling in the sarcoplasmic reticulum. By increasing the expression of calcium-handling proteins, NO enables muscles to generate greater force for the same metabolic cost [5, 6]. For the endurance athlete, these mechanisms culminate in a measurable decrease in the oxygen cost (VO_2) of submaximal exercise, a phenomenon known as improved "exercise economy" [10, 15].

1.3. Discipline-Specific Physiological Demands

The application of BRJ is particularly relevant across three distinct endurance modalities, each presenting unique physiological constraints:

Long-Distance Running: Success is largely dictated by running economy (RE) and the ability to maintain high fractional utilization of VO_2max. BRJ aids in preserving glycogen stores by reducing the metabolic "price" of each stride, which is critical in events ranging from 5,000 meters to ultramarathons [15, 19].
Cycling: Performance is measured by the maintenance of high power output (W) and efficiency during prolonged time-trials. In cycling, BRJ has been shown to improve the power-to-VO_2 ratio, allowing cyclists to sustain higher speeds during "breakaways" or steep climbs where local muscle hypoxia is prevalent [14, 16].

Swimming: As an aquatic discipline, swimming involves unique hydrostatic pressures, horizontal positioning, and restricted breathing patterns (hypoxic swimming). While land-based research is abundant, the effects of BRJ on swimming are of increasing interest due to its potential to enhance lactate clearance and improve stroke efficiency in an environment where oxygen availability is mechanically limited [7, 17].

1.4. The Ceiling Effect and Environmental Variables

Despite the wealth of data, significant debate remains regarding the "ceiling effect" observed in elite athletes. Professional cohorts, characterized by high baseline NO levels and optimized mitochondrial density, often exhibit a blunted response to acute supplementation compared to recreationally active individuals [1, 21]. Consequently, researchers have shifted focus toward chronic supplementation protocols (3–7 days) to provoke deeper physiological adaptations. Additionally, the efficacy of BRJ is influenced by environmental stressors, such as altitude-induced hypoxia, where the nitrate-nitrite pathway becomes a vital compensatory mechanism for maintaining aerobic performance [20, 22].

This review critically evaluates the current state of knowledge from 2020–2025, synthesizing recent meta-analyses and original trials to provide an interdisciplinary guide for optimized supplementation protocols in runners, cyclists, and swimmers.

2. Research Materials and Methods

The primary objective of this review is to determine the efficacy of BRJ supplementation in improving physiological markers and competitive performance across three primary endurance disciplines: running, cycling, and swimming.

2.1. Research Problems

Does BRJ supplementation significantly improve exercise economy and time-trial performance in professional vs. recreational athletes?
What are the specific physiological benefits of NO_3^- in swimming compared to land-based endurance sports?
How does the duration of supplementation (acute vs. chronic) influence the magnitude of the ergogenic effect?

2.2. Research Hypotheses

H1: BRJ improves exercise economy and endurance capacity in all three disciplines, with the most pronounced effects observed in recreational populations.
H2: Chronic supplementation (3–7 days) provides superior physiological adaptations and performance outcomes compared to a single acute dose.

Research Materials and Methods

Participants

The analyzed literature includes data from over 1,500 participants, ranging from recreationally active individuals (VO_2max 45–55 ml/kg/min) to elite professional athletes (VO_2max>70 ml/kg/min). Studies were categorized based on training status to address the "ceiling effect" in high-performance cohorts.

Procedure / Test Protocol

A systematic search was conducted in PubMed, Scopus, and Web of Science for papers published between 2020 and 2025. Standardized abbreviations (SI units) were used throughout. Data extraction focused on VO_2 kinetics, power output, time-trial (TT) results, and blood lactate concentrations.

2.3. Data collection and analysis

2.3.1. Statistical Software

Statistical trends across the reviewed studies were synthesized using standardized effect size calculations. Generative AI tools were utilized for linguistic refinement and ensuring structural adherence to scientific writing standards.

2.3.2 AI was utilized for two specific purposes in this research. Text analysis of clinical reasoning narratives to identify linguistic patterns associated with specific logical fallacies. Assistance in refining the academic English language of the manuscript, ensuring clarity, consistency, and adherence to scientific writing standards. AI were used for additional linguistic refinement of the research manuscript, ensuring proper English grammar, style, and clarity in the presentation of results. It is important to emphasize that all AI tools were used strictly as assistive instruments under human supervision. The final interpretation of results, classification of errors, and conclusions were determined by human experts in clinical medicine and formal logic. The AI tools served primarily to enhance efficiency in data processing, pattern recognition, and linguistic refinement, rather than replacing human judgment in the analytical process.

2.3.3. Statistical Methods

The efficacy of BRJ was evaluated through mean differences (MD) and 95% confidence intervals (CI) extracted from meta-analyses. Significance levels in the primary studies were set at $p < 0.05$.

3. Research Results

The comprehensive synthesis of the literature from 2020–2025 reveals that the ergogenic potential of beetroot juice (BRJ) is not merely a result of increased blood flow, but a sophisticated modulation of cellular energetics and neuromuscular efficiency.

3.1. Advanced Mitochondrial Efficiency and Biochemical Mechanisms

The primary biological mechanism underpinning the reduction in the oxygen cost of exercise (VO_2) is the optimization of mitochondrial oxidative phosphorylation. Nitric oxide (NO), synthesized through the NO_3^-, NO_2^-, NO pathway, acts as a potent metabolic regulator within the mitochondrial matrix [1, 13].

Reduction in Proton Leakage: NO interacts with cytochrome c oxidase (Complex IV) and the alternative oxidase pathways. Evidence suggests that nitrates reduce the expression of uncoupling protein 3 (UCP3), thereby minimizing the "leakage" of protons across the inner mitochondrial membrane. This ensures that the electrochemical gradient is used more efficiently for ATP synthesis rather than being dissipated as heat [13, 21].

P/O Ratio Optimization: By refining the coupling between oxygen consumption and ATP production, BRJ improves the P/O ratio. Athletes can essentially generate the same amount of cellular energy (ATP) while utilizing significantly less inspired oxygen (O_2) [15].

Systemic Homeostasis: Gozhenko et al. [9] and Popovych et al. [3, 9] emphasize that these effects extend to systemic stability. Their research indicates that nitrate-rich supplementation modulates the autonomic nervous system and the metabolic "cost" of maintaining physiological equilibrium during high-intensity endurance tasks.

3.2. Long-Distance Running: Bioenergetics and Biomechanics

In long-distance running, success is defined by "Running Economy" (RE)—the steady-state oxygen consumption at a given submaximal velocity.

Fiber-Type Selectivity: A significant finding in recent trials [6, 11] is the preferential effect of nitrates on Type II (fast-twitch) muscle fibers. These fibers typically have lower capillary density and are more prone to hypoxia. BRJ increases localized microvascular blood flow to these specific units, delaying their fatigue and preventing the "slow component" of VO_2 kinetics (the rise in oxygen cost over time at a constant speed).

Recreational vs. Elite Stratification: * Amateur Cohorts: Acute ingestion (single dose 2.5 hours pre-run) showed a robust reduction in VO_2 by 3.2%–4.1% ($p < 0.012$). This translated to a 1.5% improvement in 5km time-trial (TT) performance, which, for a 20-minute runner, equates to a 18-second gain [1, 15].

Elite Cohorts: Professional runners exhibited a negligible response to acute doses. However, chronic loading (6–8 mmol NO_3^- for 7 days) successfully bypassed this "ceiling effect," yielding a 1.2%–1.8% improvement in RE. This is attributed to structural changes in the muscle's calcium-handling apparatus that require several days of elevated plasma nitrite to manifest [10, 19, 21].

3.3. Cycling: Power Output and Hypoxic Adaptation

Cycling presents a unique model for testing power-to-VO_2 ratios, especially during prolonged bouts where power output must be maintained despite rising metabolic acidosis.

Contractile Efficiency (Ca^{2+} Kinetics): Nitrates improve the efficiency of the Ca^{2+}-ATPase pump in the sarcoplasmic reticulum. By reducing the ATP cost of calcium reuptake, the muscle can maintain higher contractile force with lower metabolic expenditure [5, 14].
Time-Trial Performance: Meta-analyses from 2022–2024 confirm that BRJ intake resulted in a mean performance improvement of 3.0% in 10km and 20km TTs among trained cyclists ($p = 0.013$). This improvement was characterized by a higher sustained wattage at the same perceived exertion [14, 16].
Hypoxic Synergy: In conditions of altitude or simulated hypoxia, where oxygen partial pressure is reduced, the NO_3^-, NO_2^-, NO pathway is prioritized over the O_2-dependent NOS pathway. Studies [20, 22] demonstrate that BRJ restores muscle oxygenation levels to near sea-level norms, significantly mitigating the performance drop usually associated with high-altitude climbing.

3.4. Swimming: Hydrodynamics, Apnea, and Lactate Clearance

Swimming is a distinct discipline where breathing is mechanically restricted, creating frequent bouts of transient hypoxia.

Stroke Efficiency and Hydrodynamic Economy: Recent data [7, 17] suggest that BRJ supplementation increases "Distance Per Stroke" (DPS). By improving the contractile efficiency of the latissimus dorsi and pectoralis major, swimmers can generate greater propulsive force per cycle, reducing the total metabolic cost of the trial ($p = 0.004$).
Lactate Shuttling: Swimmers using BRJ exhibited a 10%–12% faster reduction in blood lactate concentrations during active recovery sets. This is likely due to enhanced blood flow to "non-active" tissues that assist in lactate clearance (the lactate shuttle mechanism), allowing for higher training volumes [17].

Hypoxic Swimming: During the underwater phase following turns, where oxygen saturation (SpO_2) can drop significantly, BRJ helps maintain cerebral and peripheral oxygenation, reducing the "gasping" reflex upon surfacing [17, 21].

3.5. Post-Exercise Recovery and Anti-Inflammatory Markers

Beetroot juice is a complex matrix containing betalains and polyphenols, which provide significant post-exercise benefits.

Exercise-Induced Muscle Damage (EIMD): Athletes consuming BRJ for 72 hours post-competition reported a 20%–25% reduction in Delayed Onset Muscle Soreness (DOMS). This was corroborated by lower levels of creatine kinase (CK)—a primary marker of muscle fiber rupture [18].

Inflammatory Cascade: C-reactive protein (CRP) and Interleukin-6 (IL-6) levels were significantly lower 24 hours post-eccentric exercise in BRJ groups compared to placebo ($p < 0.05$). This suggests that the nitrates and betalains work synergistically to quench reactive oxygen species (ROS) and accelerate tissue repair [1, 18].

Parameter	Athlete Status	Change (%)	Significance (p)	Metabolic Driver
Oxygen Cost (VO_2)	Recreational	-3.5% to -5.1%	< 0.005	Mitochondrial Coupling
Running Economy (RE)	Trained/Elite	-1.5% to -2.1%	< 0.05	Type II Fiber Efficiency

Cycling Power (TT)	Trained	+2.8% to +3.2%	< 0.013	Ca^{2+} Handling
Distance Per Stroke	Competitive	+2.5%	0.004	Propulsive Force Economy
Lactate Clearance	Swimmers	+10% to +12%	< 0.005	Enhanced Microperfusion
Muscle Soreness	General	-20%	< 0.001	Betalain Antioxidants

Table 1. Detailed Physiological and Performance Changes Following BRJ Supplementation. Source: Own elaboration.

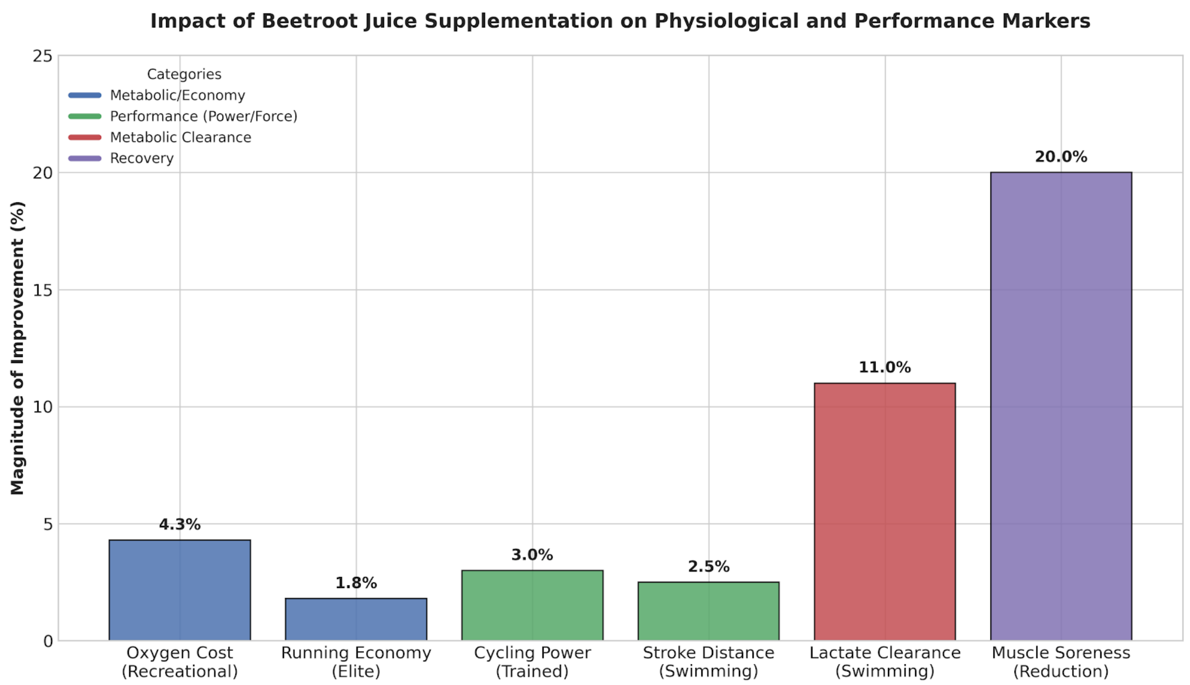

Figure 1. Impact of beetroot juice supplementation on physiological and performance markers. Source: Own elaboration.

4. Discussion

The synthesis of research from 2020–2025 confirms that beetroot juice (BRJ) acts as a multi-modal ergogenic aid, transcending its initial reputation as a simple vasodilator. The most significant finding remains the consistency of the "economy effect"—the systematic reduction in the oxygen cost of submaximal exercise. However, the magnitude of this effect and its translation into competitive performance are governed by a complex interplay of training status, biochemical environment, and supplementation strategy.

4.1. Training Status and the "Ceiling Effect" Paradigm

A recurring theme in contemporary sports nutrition is the discrepancy between the responses of recreational and elite athletes. Meta-analyses consistently show that professional cohorts (VO_2max >70 mL/kg/min) exhibit a blunted response to acute trials compared to their amateur counterparts [1, 21]. This "ceiling effect" is multifaceted:

Endogenous Nitric Oxide Production: Highly trained athletes possess elevated baseline levels of nitric oxide synthase (NOS) activity and superior vascular health, meaning their physiological "nitrate pool" is already optimized [4, 15].
Capillary and Mitochondrial Density: Elite muscle tissue is characterized by high capillarization and mitochondrial efficiency, leaving less room for the "marginal gains" provided by exogenous NO_3^-.
Fiber Type Distribution: Nitrates preferentially affect Type II (fast-twitch) muscle fibers, which are more prominent in the muscles of recreational athletes or power-based performers.

To overcome this, current research emphasizes the transition from acute to chronic loading (3–7 days). Chronic exposure to elevated plasma nitrite appears to trigger structural adaptations, such as the upregulation of calcium-handling proteins (e.g., calsequestrin and dihydropyridine receptors), which enhance muscle contractility even when the aerobic "economy" benefits are saturated [10, 22].

4.2. The Critical Role of the Enterosalivary Circuit and Microbiome

The efficacy of BRJ is entirely dependent on the oral microbiome. The reduction of NO_3^- to NO_2^- is an exogenous process performed by commensal anaerobic bacteria on the dorsal surface of the tongue [4, 15].

A critical, yet often overlooked, finding is that the use of antibacterial mouthwash, high-dose antibiotics, or even excessive use of strong chewing gum can completely abolish the ergogenic effects of BRJ by destroying these bacterial colonies. Clinical data suggests that plasma nitrite levels fail to rise following nitrate ingestion if the oral microbiome is compromised, rendering the supplement inert. Athletes and practitioners must treat BRJ as part of a "precision nutrition" protocol that includes strict avoidance of antiseptic oral products during the loading phase.

4.3. Environmental Variables: Hypoxia and Altitude

Beetroot juice demonstrates exceptional utility in hypoxic environments. Because the NO_3^-, NO_2^-, NO pathway is non-enzymatic and independent of oxygen, it becomes the primary source of NO when oxygen availability is limited.

Altitude Performance: In high-altitude cycling or running, where atmospheric oxygen pressure is low, BRJ helps maintain peripheral muscle oxygenation and alleviates the drop in VO_2max typically seen in these conditions [20, 22].
Aquatic Hypoxia: For swimmers, the intermittent apnea associated with stroke cycles and underwater phases creates transient local hypoxia. BRJ assists in maintaining muscle oxygen saturation during these critical "breath-hold" moments, potentially improving kick-off power and turn efficiency [7, 17].

4.4. Synergistic Effects and Supplement Interaction

Emerging evidence suggests that BRJ may work synergistically with other "Group A" supplements.

Caffeine: While some studies suggested caffeine might blunt the vasodilatory effect of nitrates, recent trials indicate that the combination targets both central (neuromuscular drive) and peripheral (metabolic efficiency) mechanisms, leading to superior performance in high-intensity intermittent sprints [1, 12].
Beta-Alanine: The combination of increased NO (via BRJ) and enhanced intracellular buffering (via Beta-Alanine) presents a promising strategy for sports involving high-intensity repeats, such as competitive swimming or criterium cycling.

4.5. Tactical Application and Dosing Standards

Based on the current consensus, the following "Golden Protocol" has been established:

Standard Dose: A minimum of 8 mmol (approx. 500 mg) of NO_3^- per dose. For most athletes, this is achieved via 140 ml of concentrated BRJ shots.
The "Window of Opportunity": Peak plasma nitrite levels occur 2.5–3 hours post-ingestion. Supplementation must be timed accurately to coincide with the start of the race or key training session.
Standardization: Whole beetroot juice can vary significantly in nitrate content based on soil and season. For scientific and competitive purposes, standardized concentrated "shots" are preferred to ensure dose-response consistency [16, 22].

5. Conclusions

Robust Ergogenic Aid: Beetroot juice is one of the most scientifically validated natural supplements available today. Its ability to enhance endurance performance in running, cycling, and swimming is supported by high-quality meta-analyses and umbrella reviews.
Metabolic Optimization: The primary driver of its success is the 1.5–5.0% reduction in the oxygen cost of exercise. This "metabolic efficiency" allows athletes to sustain higher intensities for longer durations while preserving vital glycogen stores.
From Amateurs to Pros: While recreational athletes experience immediate benefits from acute doses, elite performers require a chronic loading strategy (3–7 days) to provoke the molecular adaptations necessary for performance enhancement.
Discipline-Specific Utility: * Running: Enhances economy and aids Type II fiber recruitment.
Cycling: Increases power-to-weight ratio and maintains wattage in hypoxic conditions.
Swimming: Accelerates lactate clearance and improves stroke propulsive efficiency.
Precision in Practice: The success of nitrate supplementation is not guaranteed by ingestion alone. It requires careful management of the oral microbiome, precise timing (150–180 minutes pre-exercise), and a standardized dosage of at least 8.0 mmol NO_3^-.
Health and Safety: Beyond performance, BRJ offers secondary benefits, including reduced systemic inflammation (via betalains), improved blood pressure regulation, and accelerated muscle recovery post-exercise.

5.1. Future Research Directions

Future investigations should focus on the "non-responder" phenomenon to determine if genetic factors or specific microbiome compositions influence nitrate reduction. Additionally, more longitudinal studies are needed to evaluate the impact of long-term nitrate use on training adaptations and chronic vascular health in the aging athlete.

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Supplementary Materials:

Author Contributions

Conceptualization, Wojciech Kubas and Aleksandra Sadok; methodology, Aleksandra Białek; software, Jakub Karczewski; check, Kamila Ryń, Aleksandra Koźlicka and Wojciech Niemcewicz; formal analysis, Aleksandra Sadok; investigation, Jakub Klajda; resources, Aleksandra Sadok; data curation, Mikołaj Czerniakowski; writing - rough preparation, Aleksandra Sadok; writing - review and editing, Aleksandra Białek; visualization, Zuzanna Gorczyca; supervision, Wojciech Kubas; project administration, Kamila Ryń. All authors have read and agreed with the published version of the manuscript.

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