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Beetroot Juice as a Natural Ergogenic Supplement: A Literature Review of Its Effects on Physical Performance and Training Adaptation

Julia Głowacz
Medical University of Lublin
Aleje Racławickie 1, 20-059 Lublin, Poland
glowaczjulia@interia.eu
https://orcid.org/0009-0000-3564-703X

Michał Popiel
The Little Prince Hospice of Lublin
Lędzian 49, 20-828 Lublin, Poland
michal.popiel7@gmail.com
https://orcid.org/0009-0002-9726-6296

Kamil Dziekoński
Corten Dental
Makolągwy 21, 02-811 Warsaw, Poland
dziekondent@gmail.com
https://orcid.org/0009-0001-9958-1348

Jakub Rybowski
Medical University of Lublin
Student Research Group at the Chair and Department of Oral Medicine
Aleje Racławickie 1, 20-059 Lublin, Poland
jakubrybowski22@gmail.com
https://orcid.org/0009-0002-6860-7805

Sylwia Krzyśkowska
Medical University of Lublin
Student Research Group, Faculty of Medicine
Aleje Racławickie 1, 20-059 Lublin, Poland
sylwiakrzyskowska@gmail.com
https://orcid.org/0009-0001-4542-1357

Aneta Redner
Pure Clinic
Krańcowa 77, 20-356 Lublin, Poland
rednexaneta179@gmail.com
https://orcid.org/0009-0006-1404-4305

Iga Kwiecień
Medical University of Warsaw
Żwirki i Wigury 61, 02-091 Warsaw, Poland
ikwiecien8@gmail.com
https://orcid.org/0009-0008-8391-1366

Patrycja Zwierzchlewska
Medical University of Lublin
Aleje Racławickie 1, 20-059 Lublin, Poland
p.zwierzchlewska@gmail.com
https://orcid.org/0009-0005-8073-1042

Bartosz Rusin
Medical University of Lublin
Aleje Racławickie 1, 20-059 Lublin, Poland
bartek.rusin@icloud.com
https://orcid.org/0000-0002-5430-593X

Dominik Stanibuła
Medical University of Lublin
Aleje Racławickie 1, 20-059 Lublin, Poland
stanibula.dominik@gmail.com
https://orcid.org/0009-0005-9409-6430

Kacper Buczek
Medical University of Lublin
Aleje Racławickie 1, 20-059 Lublin, Poland
kbuczek@tlen.pl
https://orcid.org/0009-0005-0521-3536

ABSTRACT

Purpose: This study aims to review the current literature on the effects of beetroot juice supplementation on physical performance, training adaptation, and safety. It explores the mechanisms through which nitrates in beetroot juice enhance performance and investigates potential limitations of long-term supplementation.

Methodology: A systematic review of scientific articles was conducted, focusing on studies related to the ergogenic effects of beetroot juice. The review includes clinical trials, meta-analyses, and research on various sports disciplines and populations.

Findings: The review suggests that beetroot juice supplementation improves exercise performance by enhancing blood flow, reducing oxygen consumption, and supporting muscle recovery. However, there are some limitations regarding the effectiveness in different populations and the long-term safety of regular use.

Conclusions: Beetroot juice is a promising natural ergogenic supplement, but further research is needed to address gaps in knowledge about its effects on various athletic populations and to determine optimal dosage and supplementation protocols.

Keywords: beetroot juice, nitrates, nitric oxide, physical performance, endurance, anaerobic capacity, exercise recovery, supplementation

1. Introduction

Dietary supplementation plays a key role in supporting physical performance, recovery, and the body's adaptation to exercise. Various supplementation strategies are commonly used by athletes, both amateur and professional, including synthetic ergogenic agents and natural performance-enhancing substances. Plant-based supplements are becoming increasingly popular, as they can not only support athletic performance but also have additional health benefits.

One of the natural supplements with documented ergogenic effects is beetroot juice. Its main active ingredient is nitrates, which are converted in the body to nitric oxide (NO) - a key compound that affects the dilation of blood vessels, improved blood flow, and the efficiency of oxygen delivery to working muscles. Thanks to these mechanisms, beetroot juice can increase physical performance, reduce the energy cost of exercise, and support regeneration processes after intensive training.

The purpose of this article is to review the current research on the effect of beetroot juice on physical performance, training adaptation, and the safety of its use. Based on available scientific data, the mechanisms of action of nitrates, their effectiveness in various sports disciplines, and potential limitations resulting from long-term supplementation will be analyzed. As a result, the article will provide a comprehensive analysis of the usefulness of beetroot juice as a natural supplement supporting sports performance.

2. Methodology

The research utilized a comprehensive review of existing literature, sourcing studies from databases including PubMed, Scopus, and Google Scholar. The selection criteria were focused on clinical trials, systematic reviews, and meta-analyses that explored the effects of beetroot juice supplementation on physical performance, with particular emphasis on endurance, strength, recovery, and exercise efficiency. The review encompassed a broad range of studies involving athletes from various sports, as well as participants of differing age groups and fitness levels. Factors such as supplementation dosages, treatment durations, and demographic differences like sex and health status were also considered. The results were critically analyzed to determine the impact of beetroot juice on athletic performance, its applicability across different groups, and its overall safety. The findings were then evaluated for their relevance and potential practical applications in sports performance and recovery.

3. The Mechanics of Action

Mechanism of Nitric Oxide Production from Beetroot

The most recognized natural source of dietary NO_3^- is beetroot (Beta vulgaris), containing NO_3^- in the range of 2500 mg/kg (1), which can be converted into the bioactive form, nitric oxide (NO) (2). The mechanism of NO synthesis is thought to occur through the catabolism of arginine by the enzyme NO synthase, with arginine supplementation being shown to increase

NO levels. However, an alternative mechanism of NO generation is mediated by inorganic nitrate (NO_3^-). This means that the high amounts of NO_3^- present in beetroot juice can increase NO levels in the body. In the mouth, approximately 25% of dietary NO_3^- is reduced by NO_3^- reductase, produced by microorganisms, to nitrite (NO_2^-). This NO_2^- is then partially reduced to NO through the actions of stomach acids, after which it is absorbed in the gut. Some of this NO_2^- enters the bloodstream, and under conditions of low oxygen, such as during intense exercise, it will be further converted into NO (3).

This process highlights the potential of beetroot juice as an effective dietary source of NO, which plays a crucial role in enhancing exercise performance by improving blood flow and oxygen delivery to muscles during physical activity.

Role of Nitric Oxide in Enhancing Blood Flow and Metabolic Efficiency

Nitric oxide (NO) has a unique characteristic of vasodilation, improving blood flow and O_2 supply and modulation of energetic metabolism by reducing O_2 consumption and promoting utilization of alternative pathways (4). This vasodilation effect increases blood flow to muscle fibers promoting gas exchange. NO also induces gene expression, enhancing biogenesis and mitochondrial efficiency (3)

Muscle Fatigue and the Role of Buffering Mechanisms in Delaying Acidification

Muscle fatigue is an exercise-induced reduction in maximal voluntary muscle force (5). The rapid decline in force development during intensive exercise, referred to as fatigue, coincides with several metabolic changes occurring in the active muscle. These changes include a decline in intracellular pH, which can be considered a major factor contributing to muscle fatigue. In fact, there is an inverse and significant relationship between maximal isometric contraction force and post-effort lactic acid concentrations (6). Studies (7) have shown that this decline in pH, primarily caused by the accumulation of protons (H+) and lactate, impairs muscle function. Both H+ and lactate disrupt excitation-contraction coupling, depress calcium-activated force, and reduce tension development. This decline in intracellular pH can also modify protein conformation, alter channel properties, and depress the activity of key enzymes involved in glycolysis, which further reduces the rate of ATP resynthesis, aggravating the fatigue process.

The cellular mechanisms of proton buffering and lactate clearance represent the first line of defense against acidosis and lactate accumulation during high-intensity muscle activity. A crucial mechanism to delay pH decline and lactate accumulation in the cytosol involves buffering systems, which help to maintain cellular homeostasis and improve performance under fatiguing conditions (7). Nitric oxide (NO), through its vasodilatory effects, plays a significant role in improving blood flow, thereby aiding the removal of lactate and protons from muscles and reducing the negative effects of acidosis. NO can also reduce muscle pathology through cGMP-dependent and S-nitrosation mechanisms (8), which further contributes to improving muscle function and delaying fatigue. Moreover, NO promotes smooth muscle relaxation, and its bioavailability in the vascular system is crucial for maintaining endothelial function and promoting efficient blood circulation, which supports better delivery of oxygen and nutrients to working muscles during intense exercise. Lower NO bioavailability can impair blood flow and oxygen delivery to muscle tissues, potentially accelerating the onset of fatigue and impairing exercise performance (9). This highlights the crucial role of nitric oxide in maintaining adequate vascular function, which directly influences muscle performance and recovery during high-intensity exercise.

4. Review of Studies on the Impact of Beetroot Juice on Physical Performance

Aerobic and Anaerobic Endurance

The study by Nyberg et al. (2021) demonstrated that dietary nitrate supplementation reduces pulmonary O_2 uptake during sub maximal exercise, thereby enhancing overall exercise performance and suggesting improved aerobic efficiency. This effect highlights the potential of nitrate supplementation to increase oxygen utilization during physical activity, particularly in endurance-based activities that primarily rely on aerobic metabolism. Additionally, the study showed that nitrate and nitrite concentrations decreased in the exercising leg, implying that these ions are extracted from the arterial blood by contracting skeletal muscle. However, the precise effects of nitrate supplementation on local metabolism and blood flow regulation within contracting skeletal muscle remain unclear, necessitating further research to better understand these mechanisms (5).

These findings are consistent with those of the meta-analysis by Evangelista et al. (2024) on beetroot-based supplements (BRS), which reported a positive effect of BRS supplementation on both muscular endurance (SMD: 0.31; 95% CI: 0.10 to 0.51; $p < 0.01$) and muscular strength (SMD: 0.26; 95% CI: 0.03 to 0.48; $p < 0.05$). The analysis also highlighted that BRS supplementation was particularly effective in improving endurance performance under fatigued conditions, which aligns with Nyberg et al.'s findings on enhanced exercise performance. Both studies suggest that nitrate supplementation, such as beetroot juice, could improve oxygen utilization during exercise, particularly in endurance activities, by supporting both aerobic and anaerobic energy pathways (10).

In a separate study, Antonietto et al. (2021) examined the effects of beetroot extract supplementation on taekwondo athletes, focusing on both aerobic and anaerobic mechanisms. Their results demonstrated significant improvements in aerobic performance, including a higher absolute VO_2 peak and greater oxygen uptake at the anaerobic threshold. Moreover, they observed a notable increase in lactate concentration during the test, suggesting that beetroot extract supplementation not only enhances aerobic capacity but also contributes to performance in activities that require anaerobic energy production. These findings suggest that beetroot extract may support both aerobic endurance and anaerobic power output (11).

Additionally, a meta-analysis by Silva et al. (2022) revealed that nitrate supplementation was more effective in hypoxic conditions (coefficient: -0.045, 95% CI: -0.085, -0.005, $P = 0.028$). This indicates that beetroot juice supplementation may be particularly beneficial in environments with reduced oxygen availability, such as high-altitude training or endurance exercises conducted in oxygen-limited conditions (12).

Performance in Young Athletes

Research conducted on young athletes has shown that the initial physical condition may influence the effectiveness of beetroot juice on anaerobic performance. Recreationally active adolescents demonstrated greater strength gains after consuming beetroot juice, possibly due to lower prior physical adaptation compared to experienced athletes (13,14). However, despite these findings, there is still a limited number of studies exploring the ergogenic effects of beetroot juice supplementation in young individuals. Further research is needed to better understand how beetroot juice supplementation might affect performance across various age groups and levels of physical fitness, as well as the potential long-term benefits and safety for younger populations.

Sex-Based Differences

Exploring whether the benefits of beetroot supplementation are consistent across sexes is essential. Ortiz de Zevallos et al. (2024) proposed that inorganic nitrate intake might enhance endurance capacity in males, while females could experience a diminished response. They noted a potential differential effect of supplementation on muscle contractile function between young, healthy males and females, suggesting that the responses to such supplementation across sexes remain under-explored and require further investigation (15). On the other hand, women typically have higher NO_2 levels and a more oxidative skeletal muscle phenotype compared to men, which could make them more responsive to nitrate-rich beetroot juice. These physiological differences suggest that women may benefit more from such supplementation. However, further research is needed to better understand the specific effects of beetroot juice on female athletes and how these might differ from those observed in males (16).

Recent research by Neteca et al. (2024) has begun addressing these knowledge gaps, particularly regarding aerobic performance in female endurance athletes. Their study found significant improvements in oxygen utilization, ventilation efficiency, and heart rate regulation during exercise after beetroot juice supplementation. Specifically, VO_2 max increased by 4.82% in the beetroot juice group, while a slight decline was observed in the placebo group. These findings challenge the idea of a diminished response in females and suggest that beetroot supplementation may, in fact, enhance aerobic performance in female athletes. However, while this study provides valuable insights, it did not examine potential sex-based differences in muscle contractile function or the influence of women's higher NO_2 levels. Further research is necessary to fully understand the broader implications of beetroot supplementation across sexes, especially regarding anaerobic performance and muscle function (17).

Optimal nitrate supplementation strategy

The meta-analysis conducted by Silva et al. (2022) identified the most beneficial acute dose of inorganic nitrate, typically derived from beetroot juice, as ranging between 5 and 14.9 mmol, with the recommendation to consume it at least 150 minutes prior to exercise to optimize performance gains. Additionally, chronic supplementation protocols extending beyond two days revealed an inverse dose-response relationship, suggesting that moderate daily intake (between 5 and 9.9 mmol) is more effective than higher doses over extended periods. These findings emphasize the importance of strategic timing and dosage in nitrate supplementation to maximize its ergogenic effects (12).

The mode of nitrate ingestion also plays a significant role in its ergogenic potential. The meta-analysis revealed that beetroot juice and high-nitrate diets are more effective than nitrate salt supplements in improving exercise performance. Furthermore, the use of antibacterial mouthwash, which negatively impacts oral microbiota diversity, was found to reduce the ergogenic effects of nitrate supplementation. Since oral bacteria are essential for converting nitrate into its active forms, maintaining oral microbiota integrity is crucial for maximizing the benefits of beetroot juice supplementation (12).

Potential side effects

Although beetroot juice supplementation is commonly associated with positive cardiovascular effects, some findings suggest potential risks, particularly concerning blood pressure regulation and inflammatory responses. A systematic review by Giuriato et al. (2022) reported that dietary nitrate supplementation led to reductions in both systolic (-3.7 ±4.3 mmHg; p = 0.10) and diastolic blood pressure (-2.6 ±3.2 mmHg; p = 0.05) compared to placebo, with a more pronounced effect on diastolic blood pressure during acute interventions (-4.7 ±3.2 mmHg; n = 5; p = 0.05). While these effects may be beneficial for individuals with hypertension, they could pose risks for those with low blood pressure. The study also noted inconsistencies in the physiological effects of inorganic nitrate (iNO), particularly with high doses, raising concerns regarding safety. This highlights the need for further research to assess the long-term safety of nitrate supplementation (18).

Additional evidence reinforces the blood pressure-lowering effects of beetroot juice, particularly in hypertensive individuals. Grönroos et al. (2024) found a significant reduction in systolic blood pressure with beetroot juice supplementation, with a mean difference of -5.31 mmHg (95% CI -7.46, -3.16; I2 = 64%, GRADE ⨁⨁OO) compared to placebo. However, no significant effect was observed on diastolic blood pressure or 24-hour BP outcomes, and moderate to high heterogeneity was noted in the data. The authors concluded that daily consumption of 200-800 mg of nitrate from beetroot juice may reduce systolic blood pressure in individuals with hypertension without leading to tolerance development. Nevertheless, they cautioned that the evidence remains of low certainty, and the results should be interpreted cautiously. These findings suggest that beetroot juice could be a potential adjunct to hypertension treatment, but its clinical application requires further investigation and careful monitoring (19).

Beyond cardiovascular effects, beetroot juice supplementation may influence inflammatory responses following exercise. A systematic review and meta-analysis by Jones et al. (2022) observed a significant increase in c-reactive protein levels 48 hours post-exercise (SMD: 0.55, $p = 0.03$) compared to placebo, suggesting a potential pro-inflammatory response under certain conditions. While beetroot juice did not significantly affect markers of oxidative stress or creatine kinase ($p > 0.05$), the observed rise in c-reactive protein warrants further investigation, especially in relation to the long-term use of beetroot juice in athletes. These findings underscore the importance of considering individual health status and the specific exercise context when using beetroot juice supplementation, as its effects may vary depending on physiological conditions and dosage (20).

Comparison of beetroot juice with other supplements and their potential synergistic effects

The potential synergistic effects of combining beetroot juice with other supplements, such as caffeine, remain inconclusive. A meta-analysis by Gilsanz et al. (2024) investigated the combined effects of caffeine and nitrates on exercise performance, but found no significant additional benefits when taken together compared to their isolated intake. Specifically, the study reported that the combination of caffeine and nitrates (CAF + nitrates) did not improve performance in time trials beyond the effects of caffeine (CAF) alone ($g = -0.06$; 95% CI = -0.46 to 0.35; $p = 0.78$) or nitrates alone ($g = 0.29$; 95% CI = -0.12 to 0.70; $p = 0.17$). Additionally, no significant differences were observed in heart rate or oxygen uptake between the groups. The analysis concluded that combining CAF and nitrates did not provide extra benefits on exercise performance or physiological variables beyond what was achieved with each supplement alone. These findings suggest that while beetroot juice may have ergogenic effects, its combination with caffeine does not necessarily enhance performance beyond the effects of either supplement individually (21).

A systematic review and meta-analysis on the use of ergogenic aids by female athletes found that the effects of beetroot juice supplementation on performance are less conclusive compared to other commonly used supplements. The review highlighted that while caffeine showed positive effects on jumping performance, isometric strength, and endurance (in terms of repetitions to failure), and substances like caffeine and sodium phosphate improved sprint performance, beetroot juice did not show clear benefits for enhancing aerobic performance. Specifically, no significant effects were observed in aerobic capacity with beetroot juice supplementation, in contrast to the performance improvements associated with other supplements such as taurine, caffeine, and beta-alanine. While beetroot juice is frequently studied for its potential benefits on endurance and anaerobic performance, the findings from this meta-analysis suggest that more research is needed to confirm its effectiveness, particularly in female athletes. In contrast, supplements like caffeine and sodium phosphate have more consistently demonstrated positive effects on performance (16).

These findings underline the necessity for further research to explore the optimal use of beetroot juice in combination with other supplements, especially in female athletes, where the effects remain less clear when compared to substances like caffeine and sodium phosphate.

Conclusions

Beetroot juice supplementation has demonstrated significant potential as a natural ergogenic aid, enhancing endurance, oxygen utilization, and exercise efficiency. The conversion of dietary nitrates into nitric oxide improves blood flow, delays muscle fatigue, and supports recovery. However, the effects vary across individuals, with factors such as sex, baseline fitness level, and exercise conditions influencing outcomes. While research supports its benefits, inconsistencies in dosage, supplementation timing, and long-term safety warrant further investigation. Future studies should explore its effects on different populations, optimize dosing strategies, and assess potential interactions with other supplements to maximize its performance-enhancing potential.

Disclosure:

Author's Contribution Statement:

Conceptualization: Julia Głowacz, Michał Popiel, Kamil Dziekoński;

Methodology: Jakub Rybowski, Sylwia Krzyśkowska;

Writing - rough preparation: Julia Głowacz, Jakub Rybowski, Iga Kwiecień, Patrycja Zwierzchlewska, Kacper Buczek;
Writing - review and editing: Michał Popiel, Sylwia Krzyśkowska, Aneta Redner, Dominik Stanibuła, Bartosz Rusin, Kamil Dziekoński;
Project administration: Julia Głowacz, Michał Popiel, Iga Kwiecień, Patrycja Zwierzchlewska, Kacper Buczek;

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