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The Ergogenic Potential of Beetroot in Sports: Impacts on Endurance, Muscular Strength, and Post-Exercise Recovery

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Abstract: Beetroot has the potential to be an athlete performance booster, implying that it may enhance strength, endurance, and recovery. Beetroot supplementation, particularly in the form of beetroot juice, has gained increasing attention in sports nutrition for its potential to enhance athletic performance, endurance, and recovery. The primary bioactive compound in beetroot is dietary nitrate (NO_3^-), which is sequentially reduced to nitrite and nitric oxide (NO) in the body. This conversion promotes vasodilation, improving blood flow and oxygen delivery to muscle tissues, thereby potentially reducing fatigue and enhancing exercise efficiency. Evidence suggests that beetroot supplementation can improve cardiorespiratory endurance, delay time to exhaustion during submaximal efforts, and may enhance VO_2 max performance. Additional benefits include improved mitochondrial function and modulation of hormonal responses during exercise. While optimal dosing appears to range between 6–8 mmol of nitrate, individual variability in response has been observed, influenced by factors such as genetics and training status. Despite some inconsistencies in findings, particularly concerning anaerobic performance and muscle soreness, beetroot remains a promising ergogenic aid. To maximize its benefits, ingestion should occur 90 minutes prior to activity, aligning with peak plasma nitrate levels. Further studies are warranted to refine dosage strategies and determine long-term effects across various athletic disciplines.

Keywords: Beetroot juice, Athletes, Cardiovascular endurance, Dietary nitrate, Physiological effects

Highlights
- Dietary nitrate from beetroot juice enhances nitric oxide production, improving blood
- flow and oxygen delivery to muscles.
- Beetroot supplementation improves endurance, reduces fatigue, and may enhance recovery post-exercise.
- Mitochondrial efficiency and muscle oxygenation are positively influenced by nitrate intake.
- Peak performance effects are typically observed when beetroot juice is consumed 2–3 hours before exercise.
- Individual responses to beetroot supplementation vary based on genetics, baseline nitrate intake, and training status.
- Optimal dosing ranges from 6–8 mmol of nitrate for performance enhancement.
- Additional research is needed to confirm its effects across different sports and athlete populations.

I. INTRODUCTION

Enhancing athletic performance has long been a central focus in both competitive and recreational sports. Athletes and coaches continually seek strategies to improve **physiological efficiency, muscular strength, endurance capacity**, and **post-exercise recovery**. In this context, **ergogenic aids**—substances or techniques used to enhance physical performance—have garnered widespread attention. While synthetic ergogenic aids such as creatine, caffeine, and beta-alanine are well-established, growing emphasis is being placed on **natural, food-based alternatives** that offer functional health benefits alongside performance support (Maughan et al., 2018).

One such alternative is **beetroot (Beta vulgaris) juice**, which has emerged as a promising **natural ergogenic aid** due to its high concentration of **inorganic nitrate (NO_3^-)**. Once ingested, nitrate undergoes **enterosalivary circulation**, where it is reduced to **nitrite (NO_2^-)** by oral bacteria and subsequently converted to **nitric oxide (NO)**—a critical signaling molecule involved in **vasodilation, mitochondrial respiration, muscle contractility**, and **metabolic efficiency** (Lidder & Webb, 2013; Jones, 2014). These effects collectively enhance **oxygen delivery and utilization**, key determinants of athletic endurance and recovery.

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Beyond its nitrate content, beetroot is considered a **functional food** with antioxidant, anti-inflammatory, and endothelial-supporting properties, which may contribute to reduced exercise-induced oxidative stress and inflammation. This has made beetroot particularly appealing to athletes seeking performance gains through safe, plant-based, and **non-pharmacological interventions**. (Domínguez et al., 2017).

II. PHYTOCHEMICAL PROFILE OF BEETROOT

Beetroot (*Beta vulgaris*) is a nutrient-rich root vegetable recognized for its potent phytochemical composition, which contributes to both its vibrant color and its physiological benefits, particularly in athletic performance. The primary bioactive constituents in beetroot include **dietary nitrates**, **betalains**, **polyphenols**, and **antioxidants**, each playing a role in enhancing vascular function, reducing oxidative stress, and supporting overall metabolic health (Clifford et al., 2015).

Among these, **nitrate (NO_3^-)** is the most prominent and functionally relevant compound for ergogenic purposes. Upon ingestion, dietary nitrate undergoes a bioconversion process, first being reduced to **nitrite (NO_2^-)** by commensal bacteria in the oral cavity, and then further reduced to **nitric oxide (NO)** in the stomach and peripheral tissues (Jones, 2014). This **nitrate–nitrite–NO pathway** enhances endothelial function through vasodilation, leading to improved blood flow, oxygen delivery, and muscular efficiency during exercise (Lidder & Webb, 2013). These effects are particularly valuable during hypoxic conditions, high-intensity activities, or endurance sports where oxygen economy is critical.

In addition to nitrates, beetroot is rich in **betalains**, a class of nitrogen-containing pigments such as betanin and vulgaxanthin, known for their strong antioxidant and anti-inflammatory properties (Georgiev et al., 2010). These compounds help mitigate oxidative stress and inflammation that commonly follow intense physical exertion. **Polyphenols**, including phenolic acids and flavonoids, further support antioxidant defenses, while **vitamin C**, manganese, and other micronutrients add to beetroot's nutritional profile.

The **bioavailability of dietary nitrate** depends on several factors, including the form of ingestion (juice vs. whole beet), oral microbiota composition, and timing relative to exercise. Studies suggest that peak plasma nitrate and nitrite concentrations occur approximately **2 to 3 hours after consumption**, making timing crucial for maximizing performance benefits (Wylie et al., 2013). Additionally, the use of antibacterial mouthwash can inhibit nitrate-reducing oral bacteria, thereby impairing nitric oxide production and its downstream effects (Govoni et al., 2008).

III. MECHANISM OF ACTION

The ergogenic effects of beetroot primarily arise from the **nitrate–nitrite–nitric oxide (NO) pathway**, a non-enzymatic route distinct from endogenous NO synthesis via nitric oxide synthase (NOS). Upon ingestion, **dietary nitrate (NO_3^-)** is absorbed in the upper gastrointestinal tract and concentrated in the salivary glands. Oral bacteria play a crucial role in reducing nitrate to **nitrite (NO_2^-)**, which is then swallowed and further reduced to **NO** in the acidic environment of the stomach and peripheral tissues, particularly under hypoxic or acidic conditions common during intense exercise (Lundberg et al., 2008).

Nitric oxide (NO) acts as a potent **vasodilator**, relaxing vascular smooth muscle and increasing blood flow to working muscles. This vasodilation enhances **oxygen delivery and nutrient transport**, improving **muscle oxygenation**, especially during submaximal and endurance-type exercises (Bailey et al., 2009). These effects contribute to a **reduction in the oxygen cost** of exercise, delaying fatigue, and improving performance.

Furthermore, NO has a significant influence on **mitochondrial efficiency**. It modulates mitochondrial respiration by enhancing oxidative phosphorylation and reducing proton leak, which improves the **ATP yield per oxygen molecule consumed** (Larsen et al., 2011). This effect contributes to improved **aerobic performance**, allowing athletes to sustain high-intensity efforts for longer durations.

Beyond vascular and metabolic roles, nitric oxide influences **neuroendocrine and hormonal responses**. It regulates the release of key **anabolic hormones** such as growth hormone and testosterone and interacts with **stress mediators** like cortisol through the hypothalamic-pituitary-adrenal (HPA) axis (Krause et al., 2011). NO also modulates **neurotransmission**, contributing to improved motor unit recruitment and muscular coordination, which can be advantageous in both endurance and power-based sports.

Together, these physiological effects explain the growing interest in beetroot supplementation as a **natural ergogenic aid**, offering multifaceted benefits ranging from vascular support to metabolic efficiency and neuroendocrine balance.

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IV. ENDURANCE AND PERFORMANCE OUTCOMES

Beetroot juice supplementation has garnered significant attention for its capacity to enhance athletic endurance and performance, particularly in aerobic and submaximal activities. The ergogenic effects are largely attributed to its high dietary nitrate content, which improves physiological efficiency during exercise.

4.1. Improved Time to Exhaustion

Numerous studies have demonstrated that dietary nitrate intake from beetroot juice increases **time to exhaustion**, enabling athletes to sustain physical efforts for longer periods. For instance, Bailey et al. (2009) reported a **16% improvement in exercise tolerance** during high-intensity cycling following beetroot juice supplementation. This increase was attributed to reduced oxygen cost and enhanced muscle efficiency, particularly during submaximal efforts.

4.2. Influence on VO_2max and Submaximal Performance

While the impact of beetroot juice on **VO_2max** (maximum oxygen uptake) remains inconclusive in highly trained athletes, its benefits are evident in submaximal performance. Lansley et al. (2011) observed that beetroot juice reduced the oxygen demand during moderate-intensity exercise, which resulted in improved **exercise economy** and a longer duration of sustained effort without increasing oxygen consumption. These findings are particularly significant for endurance athletes seeking to optimize performance without incurring greater metabolic strain.

4.3. Effects on Anaerobic Threshold and Exercise Economy

Beetroot supplementation may also influence the **anaerobic threshold**, the exercise intensity at which lactate begins to accumulate in the blood. By improving oxygen availability and muscular efficiency, beetroot juice can delay the onset of fatigue associated with anaerobic metabolism. Vanhatalo et al. (2010) found that dietary nitrate extended the **work rate range** over which athletes could exercise aerobically, indicating a shift in the **anaerobic threshold**.

Additionally, **exercise economy**, defined as the oxygen cost at a given exercise intensity, is improved through nitrate-induced reductions in mitochondrial oxygen consumption and enhanced ATP production efficiency (Larsen et al., 2007). This translates into more efficient muscle contractions and better overall endurance performance.

V. RECOVERY AND MUSCLE SORENESS

Beetroot juice supplementation has been explored not only for performance enhancement but also for **post-exercise recovery and reduction of muscle soreness**. The anti-inflammatory and antioxidant properties of beetroot, primarily due to its **betalains, polyphenols, and nitrate content**, play a key role in mitigating muscle damage and oxidative stress.

5.1. Reduction of Muscle Damage and Inflammation

Exercise, particularly of high intensity or eccentric in nature, induces muscle fiber microtrauma and inflammation. Clifford et al. (2016) demonstrated that beetroot juice supplementation significantly reduced **markers of muscle damage**, such as creatine kinase, and improved **functional recovery** post-exercise. The antioxidants in beetroot reduce oxidative stress, which is a major contributor to delayed onset muscle soreness (DOMS).

5.2. Improved Recovery Dynamics

Beetroot juice may facilitate faster **recovery of muscle function** and performance by improving blood flow and nutrient delivery to tissues. A study by Clifford et al. (2017) reported enhanced **recovery of peak torque and range of motion** in participants following repeated sprint exercises, suggesting a protective and regenerative effect of beetroot bioactives.

VI. INTER-INDIVIDUAL VARIABILITY IN RESPONSE

While many athletes benefit from beetroot supplementation, **responses vary widely** across individuals due to several physiological and genetic factors.

6.1. Influence of Genetic and Microbiota Factors

The effectiveness of dietary nitrate largely depends on its **conversion to nitrite by oral bacteria**. Variability in the oral microbiome significantly influences **nitrate bioactivation** (Jones et al., 2018). Additionally, **genetic polymorphisms** in nitric oxide synthase enzymes and differences in baseline nitric oxide levels may contribute to differing outcomes among individuals.

6.2. Training Status and Baseline Fitness

The **training status** of the individual also plays a crucial role. While recreational and moderately trained individuals often exhibit clear performance gains, **elite athletes** may show **blunted or minimal improvements**, likely due to their already optimized physiological systems (Wilkerson et al., 2012). This suggests a **ceiling effect** for nitric oxide-mediated performance enhancement.

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6.3. Dose and Timing Considerations

Variability may also stem from inconsistent **dosing strategies** and timing of ingestion. The peak plasma nitrate concentration typically occurs **2–3 hours post-ingestion**, making **timing critical** for performance benefits (Wylie et al., 2013). Insufficient dosing (below 6–8 mmol nitrate) may also lead to diminished effects.

VII. VARIABILITY IN ATHLETIC PERFORMANCE OUTCOMES

Although numerous studies highlight the ergogenic potential of beetroot, the degree of improvement in athletic performance varies considerably among individuals. This **inter-individual variability** has important implications when interpreting performance outcomes related to endurance, strength, and recovery.

7.1. Genetic and Microbiota Influences

Performance outcomes following beetroot supplementation are partly influenced by **genetic polymorphisms** associated with nitric oxide (NO) synthesis and vascular responsiveness. Variants in genes such as *NOS3* may affect endothelial NO production, thus modulating the cardiovascular and muscular benefits derived from dietary nitrate (Jones et al., 2018). Additionally, the **oral microbiota**, essential for converting dietary nitrate to nitrite, plays a critical role in NO bioavailability. The use of antiseptic mouthwash or an altered oral microbiome can significantly impair this conversion, reducing the physiological effects of beetroot (Vanhatalo et al., 2018; Woessner et al., 2016).

7.2. Training Status and Performance Gains

Beetroot's ergogenic effects appear to be **more pronounced in recreational and moderately trained individuals** than in elite athletes. This may be due to the relatively greater margin for physiological improvement in less-trained individuals, particularly regarding oxygen efficiency and mitochondrial function (Porcelli et al., 2015). In contrast, elite athletes may already exhibit optimized performance capacities, diminishing the observable benefits of supplementation (Wilkerson et al., 2012).

7.3. Baseline Nitrate Intake and Lifestyle Factors

Habitual **dietary nitrate intake** also influences the magnitude of performance enhancement. Individuals with high baseline consumption of nitrate-rich vegetables may have limited additional benefit from supplementation due to already elevated plasma nitrate/nitrite levels (Hezel & Weitzberg, 2015). Moreover, **lifestyle factors**—such as smoking, physical inactivity, and poor cardiovascular health—can impair NO metabolism, potentially blunting the ergogenic effect of beetroot (Lundberg et al., 2009). Table 1 contents the details of factors contributing to variability in beetroot supplementation response with key references.

Table 1: Factors Contributing to Variability in Beetroot Supplementation Response

Factor	Description	Impact on Response	Key References
Genetic Polymorphisms	Variants in genes (e.g., *NOS3*) affect NO production and endothelial function	Alters vasodilation and oxygen delivery efficiency	Jones et al., 2018
Oral Microbiota Composition	Oral bacteria reduce nitrate to nitrite; influenced by hygiene, mouthwash use, or antibiotics	Essential for NO production; disruptions can impair physiological benefits	Hezel & Weitzberg, 2015; Vanhatalo et al., 2018
Training Status	Fitness level affects mitochondrial efficiency and oxygen utilization	Recreational athletes respond more favorably than elite athletes	Porcelli et al., 2015; Wilkerson et al., 2012
Baseline Nitrate Intake	Regular intake from vegetables may elevate baseline plasma nitrate	High habitual intake may reduce additional benefit from supplementation	Hezel & Weitzberg, 2015
Dietary Habits	Overall dietary composition (e.g., antioxidants, fiber, fat) may modulate nitrate metabolism	May influence absorption, bioavailability, and NO production	Lundberg et al., 2009

Lifestyle Factors	Smoking, physical inactivity, and pollution exposure affect vascular and NO function	May reduce effectiveness of nitrate supplementation	Lundberg et al., 2009
Use of Antibacterial Products	Mouthwash and antibiotics alter oral microbiome	Inhibits conversion of nitrate to nitrite, lowering NO availability	Woessner et al., 2016
Age and Sex	Hormonal and physiological differences may affect nitrate metabolism	Variable effects across demographic groups	Jones et al., 2018

VIII. PRACTICAL APPLICATIONS AND FUTURE PERSPECTIVES

8.1. Dosing Strategies and Timing

Harnessing the ergogenic benefits of beetroot requires careful attention to dosing and timing. Most positive outcomes have been observed with nitrate doses in the range of **6–12 mmol**, typically provided by consuming **~500 mL of beetroot juice** or its concentrated equivalents **2 to 3 hours before exercise** (Jones et al., 2014; Wylie et al., 2013). This timing aligns with the peak in plasma nitrite levels, optimizing nitric oxide (NO) availability during physical exertion.

Chronic supplementation regimens—ranging from **3 to 15 days**—may provide cumulative improvements in **mitochondrial efficiency and endothelial function**, especially in trained endurance athletes (Domínguez et al., 2017). For more personalized use, **body weight-adjusted dosing (~0.1 mmol/kg)** has been suggested to standardize exposure across individuals (Hoon et al., 2013). However, defining the optimal **acute vs. chronic** strategies across different athletic contexts remains an open area for investigation.

8.2. Safety and Tolerability

Beetroot supplementation is generally **safe and well-tolerated** in healthy individuals, with only minor side effects such as **beeturia** and **gastrointestinal discomfort** at higher doses. Concerns over nitrate's potential to form harmful nitrosamines are largely **mitigated by the presence of antioxidants and polyphenols** in vegetable-based sources (Hord et al., 2009; Lidder & Webb, 2013).

Caution is advised for individuals with **renal impairment** or **hypotension**, and athletes should avoid **antibacterial mouthwashes** before or after ingestion, as these can disrupt **nitrate-reducing oral bacteria**, diminishing the supplement's effectiveness (Kapil et al., 2013).

8.3. Emerging Formulations

The evolution of beetroot supplementation has moved beyond traditional juice to include **standardized powders, chews, gels, and encapsulated nitrate formulations**, offering athletes **convenience, dose precision, and reduced gastrointestinal burden** (de Castro et al., 2019). Furthermore, **co-formulation** with polyphenols or adaptogenic compounds may enhance performance benefits, though these synergies remain underexplored.

Emerging technologies, such as **nanoparticle-based carriers** and **slow-release nitrate delivery systems**, aim to extend nitrate availability and improve its synchronization with prolonged physical exertion (Petróczi et al., 2022).

8.4. Research Gaps and Future Directions

Despite a growing evidence base, important **knowledge gaps** persist that warrant future exploration:

- **Long-term safety and efficacy** in elite athlete populations remain inadequately studied.
- There is a paucity of data on **female athletes**, who may exhibit distinct responses due to sex-specific hormonal influences (Bond et al., 2022).
- The effectiveness of beetroot in **non-endurance contexts** (e.g., strength training, intermittent sports) is underrepresented.
- The **role of the oral and gut microbiome** in modulating nitrate bioactivation requires deeper mechanistic study.
- **Interactions with other ergogenic aids** (e.g., caffeine, creatine) are inconsistently reported and merit controlled trials (Peeling et al., 2018).

In addition, future studies should aim to:

- Utilize **genomic and metabolomic profiling** to identify responders and non-responders.
- Evaluate **real-world performance metrics** using wearable technology and ecological trial designs.
- Investigate **timing strategies** around competition and training cycles to optimize outcomes.

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IX. CONCLUSION

Beetroot supplementation has emerged as a **scientifically validated, natural ergogenic aid**, with growing appeal among athletes seeking performance and recovery enhancements without reliance on synthetic compounds. Its **high nitrate content**, coupled with antioxidant and anti-inflammatory properties, positions beetroot as a **multifunctional tool** for improving **oxygen delivery, muscular efficiency, and recovery kinetics**.

Optimal **dosing strategies**, formulation innovations, and a strong safety profile make beetroot a **practical and accessible option** across various levels of sport. However, **individual variability**, **incomplete mechanistic understanding**, and a **limited scope of application-specific evidence** highlight the need for continued research.

As sports nutrition advances toward **personalized and precision-based interventions**, beetroot represents a promising candidate for integration into tailored performance-enhancement strategies. Future research should bridge current gaps, embrace technological tools, and expand the utility of beetroot across **diverse athletic populations and performance domains**.

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