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SELECTED DIETARY SUPPLEMENTS AND THEIR IMPACT ON ENDURANCE AND RECOVERY IN RUNNERS: A SYSTEMATIC REVIEW

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ABSTRACT

Running places high metabolic, neuromuscular and physiological demands on athletes, stimulating interest in nutritional supplements that may enhance performance and delay fatigue. Various ergogenic aids - including caffeine, creatine, β-alanine and beetroot-derived nitrates, have been investigated, yet their relative effectiveness across different running modalities remains unclear. A systematic search of PubMed (2010–2025) using the terms "supplementation" and "running" identified 234 records. After screening titles, abstracts and full texts according to predefined criteria, 26 studies evaluating single-ingredient supplements and reporting running-specific outcomes were included. A narrative synthesis was conducted due to heterogeneity in study designs and performance tests. Caffeine consistently improved running performance across sprint, repeated and endurance efforts by extending time to exhaustion, enhancing acceleration and increasing metabolic activation without elevating physiological strain. Creatine improved mean power, maintained running speed and reduced fatigue during short and repeated high-intensity efforts, with limited effects in endurance running. β-alanine increased muscle carnosine content and enhanced tolerance to high-intensity or fatigue-inducing exercise, while producing modest improvements during submaximal workloads. Beetroot-derived nitrates improved performance primarily in short, intense and intermittent running, especially in moderately trained athletes, whereas betalains supported recovery through antioxidant and anti-inflammatory mechanisms. Caffeine, creatine, β-alanine and beetroot-derived supplements all exert ergogenic effects, but their benefits are exercise-specific. Matching the supplement to the running demands and athlete characteristics is essential for maximizing performance outcomes.

KEYWORDS

Supplementation, Runners, Caffeine, Creatine, Nitrates, β-alanine, Beetroot Juice

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Introduction

Running is one of the most widely practiced forms of endurance and competitive sport, placing high physiological demands on energy metabolism, muscle buffering capacity, neuromuscular efficiency and oxygen delivery. As a result, nutritional supplementation has gained considerable interest as a strategy to improve performance, delay fatigue and optimize physiological responses during both high-intensity and prolonged running efforts.

Current literature indicates that several supplements may enhance exercise performance through distinct mechanisms. β-alanine increases intramuscular carnosine content and improves buffering capacity during high-intensity exercise, as demonstrated by meta-analytic evidence showing performance benefits in efforts lasting 1–4 minutes [1]. Creatine supplementation increases phosphocreatine availability and enhances high-intensity exercise capacity and muscle hypertrophy when combined with resistance training, although adaptations vary by tissue, age and training status [2]. Dietary nitrates from beetroot juice elevate plasma nitrite and nitric oxide bioavailability, reduce the oxygen cost of exercise and improve tolerance to severe-intensity workloads, with effects dependent on dose and physiological context [3]. In addition, broader lifestyle and nutritional interventions, including antioxidant-rich foods and micronutrient strategies, have been explored as modulators of exercise adaptation, though findings remain mixed and context-dependent [4].

Despite substantial interest, existing studies vary widely in design, supplement dosage, training status of participants and performance tests used. Moreover, supplements are often examined in isolation, and findings are not directly compared across different classes of ergogenic aids. This creates a gap in understanding how commonly used supplements such as caffeine, creatine, β-alanine and beetroot-derived nitrates differ in their efficacy across various forms of running performance.

Therefore, the aim of this work is to synthesize and compare the ergogenic effects of four widely used supplements – caffeine, creatine, β-alanine and beetroot-derived compounds – on running performance, drawing on evidence from the past 15 years. This review seeks to clarify their mechanisms, identify performance contexts in which they are most effective and highlight differences related to exercise intensity and athlete training status.

Methodology

A literature search was conducted using the PubMed database to identify studies examining the effects of supplementation on running performance. The search covered the period from 2010 to 2025. The following keywords were used individually and in combination: “supplementation” and “running.” The initial search yielded 234 articles. Titles and abstracts were screened for relevance based on predefined inclusion criteria: (1) human participants, (2) running-specific performance outcomes, and (3) evaluation of an ergogenic supplement. After full-text assessment, 26 articles meeting all criteria were included in the final analysis. No restrictions were placed on participant sex, age, or performance level. The selected studies were then synthesized to evaluate the effects of different supplements on various forms of running performance.

Results

Caffeine

Four studies examining the ergogenic effects of caffeine in runners were analyzed, with particular emphasis on its impact on performance-related physiological parameters. The included experiments covered both sprint efforts and long-distance running, allowing for an evaluation of caffeine’s effectiveness across different types of running activity.

In the study by Ping et al., nine runners completed two running trials in a hot and humid environment. In each trial, participants ingested either 5 mg/kg of caffeine or a placebo one hour before exercise. They then performed treadmill running at 70% VO_2max, during which heart rate, core temperature, and perceived exertion were measured. The results showed that after consuming caffeine, the runners continued running to exhaustion significantly longer than after placebo. At the same time, caffeine did not affect heart rate, core temperature, or perceived exertion. This indicates that caffeine improved endurance without increasing physiological strain under challenging thermal conditions [5].

In the study by Matsumura et al., thirteen sprinters performed two 100-meter sprint trials in field conditions. In each trial, athletes ingested either 6 mg/kg of caffeine or placebo in capsule form, and then completed a sprint in which their running velocity was recorded across successive sections of the distance, with particular attention to the acceleration phase. The results demonstrated that after caffeine ingestion, participants achieved significantly better sprint times—on average 0.14 seconds faster than after placebo—with the greatest improvement occurring in the first 60 meters. This suggests enhanced power output and force-generation capacity during the initial phase of the sprint, consistent with the neuromuscular mechanism of caffeine’s action [6].

In the study by Liu et al., runners performed two 1000-meter runs separated by a 20-minute recovery period after ingesting caffeine (6 mg/kg), placebo, or other supplements. Heart rate and blood lactate concentration were monitored during both trials to assess caffeine’s effect not only on performance itself but also on the ability to repeat high-intensity exercise. The results demonstrated that participants who consumed caffeine achieved better performance in the second run compared with the placebo condition. They also displayed higher lactate levels and elevated post-exercise heart rate. This indicates increased metabolic activation and suggests that caffeine may help sustain high-intensity output during repeated efforts, for example through enhanced glycolysis and faster recruitment of fast-twitch muscle fibers [7].

In the meta-analysis by Wang et al., 21 randomized studies examining the effects of caffeine on running performance were analyzed, including both time-to-exhaustion tests and fixed-distance time trials. The researchers considered participants with different training levels and a wide range of caffeine doses used across the experiments. The analysis showed that caffeine significantly increases time to exhaustion and produces a small but meaningful improvement in time-trial performance—regardless of the runners’ training status. This indicates a moderate yet consistent ergogenic effect. The authors emphasize that the beneficial action of caffeine arises from both central mechanisms (adenosine receptor antagonism and reduced perception of fatigue) and peripheral mechanisms (increased calcium availability in muscle tissue and enhanced mobilization of free fatty acids), which together explain the simultaneous improvement in aerobic and anaerobic performance [8].

Creatine

Four studies evaluating the ergogenic effects of creatine on runners were analyzed. The experiments included both sprint efforts and long-distance endurance running, allowing assessment of creatine's effects across different types of running activity.

In the study by Deminice et al., soccer players performed a repeated RAST test consisting of six 35-meter sprints with short recovery intervals, before and after seven days of creatine supplementation at a dose of 0.3 g/kg or placebo. After supplementation, participants showed clearly higher mean, peak, and minimum power values compared with the placebo group. At the same time, creatine reduced the post-exercise increase in inflammatory markers such as TNF-α and CRP, indicating a beneficial effect on the inflammatory response induced by high-intensity sprinting. In contrast, there was no reduction in oxidative stress markers, which increased similarly to the placebo condition [9].

In the study by Tyka et al., the effects of six weeks of creatine malate supplementation were evaluated in sprinters and long-distance runners. Among sprinters, supplementation led to significant increases in peak power, total work, and anaerobic performance in the Wingate test, as well as higher post-exercise growth hormone levels. In long-distance runners, improvements were observed in the distance covered during the endurance test, although VO_2max and anaerobic parameters remained unchanged. These findings suggest that creatine exerts stronger ergogenic effects in sprinters than in endurance runners [10].

In the study by Bogdanis et al., sixteen men completed a protocol of six 10-second non-motorized treadmill sprints following five days of creatine supplementation (75 mg/kg/day) or placebo. Creatine did not affect peak power; however, it significantly improved mean power and running speed during the final seconds of the sprints and in the last repetitions of the test. Additionally, lower post-exercise blood ammonia levels were observed, which may indicate reduced purine nucleotide degradation despite the higher running intensity. Glycolytic and aerobic parameters remained unchanged [11].

In the study by Huerta Ojeda et al., soccer players underwent 14 days of creatine supplementation (0.3 g/kg/day) and subsequently performed a repeated 30-meter sprint test combined with additional interventions (caffeine, variable resistance). The results did not show significant differences in sprint times or fatigue parameters between the groups, suggesting no cumulative effect of creatine with other ergogenic aids under a highly complex testing protocol. However, the authors emphasized substantial individual variability in the response to creatine supplementation [12].

Beta-alanine

Research on the effects of β-alanine in runners has focused primarily on its role in high-intensity exercise and in efforts where resistance to accumulating fatigue is crucial. The analyzed studies included both repeated-sprint protocols and endurance-oriented tests, allowing for an assessment of how increased muscle carnosine content may influence performance across different types of running activity.

Milioni and colleagues conducted a 10-week training intervention in which trained men completed high-intensity interval training (HIIT), with β-alanine or placebo introduced during the final six weeks. Participants received 6.4 g/day of β-alanine or a matched placebo while following identical training routines. Supplementation led to clear improvements in repeated-sprint performance, reflected in reduced total, best, and mean sprint times, as well as elevated post-exercise blood lactate levels. Muscle biopsies confirmed substantial increases in carnosine concentrations exclusively in the β-alanine group, accompanied by lower neuromuscular fatigue following sprint testing. These outcomes indicate that β-alanine enhanced buffering capacity and improved fatigue tolerance during repeated maximal efforts [13].

In the study by Marko et al., adolescent middle- and long-distance runners consumed β-alanine (4.8–6.4 g/day) or placebo for four weeks during regular training. Although no significant improvements in VO_2peak were observed, β-alanine supplementation increased time to exhaustion by 6.5%, compared to a negligible improvement in the placebo group. Additionally, runners supplementing β-alanine exhibited small but favorable changes in metabolic and ventilatory responses at a fixed submaximal workload, suggesting reduced physiological strain during steady-state exercise [14].

These findings indicate that β-alanine reliably elevates muscle carnosine stores and enhances performance in high-intensity or fatigue-inducing conditions, whereas its influence on long-duration aerobic capacity appears modest and highly dependent on the specific performance context.

Beetroot Juice and Dietary Nitrates

To investigate the effects of beetroot juice and nitrate supplementation on athletic performance, twelve scientific studies were analyzed. In the study by Lansley et al., nine trained men consumed either beetroot juice containing 6.2 mmol of nitrate or nitrate-depleted beetroot juice for six days in a randomized, double-blind study. After the supplementation period, participants completed treadmill walking and running tests at moderate and high intensities. The results showed that nitrate supplementation significantly reduced the oxygen cost of walking and submaximal running and increased time to exhaustion during high-intensity running by approximately 15% compared to placebo. A significant increase in plasma nitrite concentration and a reduction in systolic blood pressure were also observed [15].

In the study by Esen et al., the authors evaluated the acute effect of a single high dose of beetroot juice (140 mL, ~12.8 mmol NO_3^-) on performance in the Prone Yo-Yo IR1 test (a modified repeated sprint test performed from a prone starting position, followed by 2 × 20 m shuttle runs at increasing speeds, with 10-second rest intervals) in 12 professional rugby players in a randomized crossover study. Despite a significant rise in plasma nitrate and nitrite concentrations, supplementation did not improve the distance covered in the test. These findings suggest that acute nitrate supplementation may not provide performance benefits in high-intensity intermittent running among professional athletes [16].

In another experiment, Porcelli et al. examined the response of runners with different training statuses to nitrate supplementation. They showed that individuals with lower VO_2max demonstrated substantially greater improvements in exercise parameters such as time to exhaustion and oxygen cost compared with highly trained athletes. The increase in plasma nitrite concentration after supplementation was also markedly higher in less trained runners, suggesting a greater physiological sensitivity to the intervention in this group [17].

In the study by Clifford et al., a randomized, double-blind trial was conducted in which 34 experienced marathon runners completed a marathon and were subsequently assigned to receive either beetroot juice (BTJ) or a placebo (PLA) for three days. Measurements were taken before the race, immediately after, and on days 1 and 2 post-race. Assessments included isometric strength (MIVC), countermovement jump height (CMJ), muscle soreness, leukocyte count, and markers of muscle damage and inflammation (CK, AST, hs-CRP, IL-6, IL-8, TNF-α). Supplementation began only after the marathon, and each group consumed seven servings within 48 hours. The results showed that the marathon induced a marked decrease in muscle function: both CMJ and MIVC dropped significantly immediately after the run ($p < 0.0001$), and CMJ remained reduced on days 1 and 2. However, no differences were found between the BTJ and placebo groups, and isometric strength returned to baseline levels in both groups by day 2. Muscle soreness increased immediately post-race and resolved by day 2, again without group differences. The marathon elicited a typical inflammatory and hematological response: leukocyte count increased 1.7-fold immediately after the race and remained elevated through day 2 ($p < 0.0001$), with similar patterns for neutrophils and monocytes, but BTJ did not influence these changes. CK and AST rose significantly, peaking on day 1, and hs-CRP remained elevated through day 2 in both groups - again with no effect of BTJ. Similarly, IL-6, IL-8, IL-10, and TNF-α rose sharply post-race ($p < 0.0001$), with IL-6 remaining slightly elevated until day 1. No inflammatory or muscle damage marker, including MCP-1, was affected by BTJ supplementation. Three-day beetroot juice supplementation following the marathon did not reduce muscle damage or inflammation, nor did it accelerate recovery of muscle function. The authors suggest that the lack of effect may be due to the relatively modest degree of muscle damage in this well-trained cohort, leaving limited room for measurable improvement [18].

The study by Montenegro et al. used a randomized, double-blind, placebo-controlled crossover study in which 22 triathletes (13 women, 9 men) completed two exercise protocols, each preceded by six days of supplementation with beetroot-derived betalain capsules (BRC, 100 mg/day) or placebo. On day seven, participants ingested an additional 50 mg dose and then completed 40 minutes of cycling at 75 ± 5% VO_2max, followed by a 10 km running time trial. After 24 hours, they returned to the laboratory to perform a 5 km time trial as a recovery assessment. Running time, heart rate, perceived exertion (RPE), creatine kinase (CK), and subjective fatigue (BFI) were measured. The results showed that the 10 km time trial was significantly faster after BRC supplementation (49.5 ± 8.9 vs. 50.8 ± 10.3 min; $p = 0.03$), despite no differences in heart rate or RPE, suggesting improved performance without increased physiological or perceptual cost. In the recovery trial, the 5 km time was also faster after BRC (23.2 ± 4.4 vs. 23.9 ± 4.7 min; $p = 0.003$), with 17 of 22 participants improving relative to placebo. BRC also attenuated the rise in CK after the 10 km trial (40.5 ± 22.5 vs. 49.7 ± 21.5 UL^{-1}; $p = 0.02$) and reduced the increase in fatigue over the following 24 hours (–0.05 ± 6.1 vs. 3.23 ± 6.1; $p = 0.05$), indicating less muscle damage and faster recovery. These findings suggest that betalain-rich extract from beetroot (independent of nitrates) enhances endurance performance and promotes recovery, likely due to its antioxidant and anti-inflammatory properties [19].

In the Nyakayiru study, a randomized, double-blind, placebo-controlled crossover design was used to evaluate the effects of six days of nitrate-rich beetroot juice supplementation on performance in 32 well-trained soccer players (23 ± 1 years). Participants consumed 140 mL of beetroot juice (~800 mg nitrate) or nitrate-depleted juice daily, with at least an eight-day washout between conditions. On the final day, blood and saliva samples were collected to measure nitrate/nitrite levels, after which players completed the Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1), with heart rate monitored throughout. Supplementation significantly increased plasma and salivary nitrate and nitrite concentrations ($p < 0.001$) and led to a 3.4% increase in distance covered (1574 ± 47 vs. 1623 ± 48 m; $p = 0.027$). Average heart rate during the test was also lower (172 ± 2 vs. 175 ± 2 bpm; $p = 0.014$). No differences were found in VO_2 or other physiological markers. The findings indicate that six-day nitrate supplementation improves the ability to perform repeated high-intensity efforts, likely through enhanced nitric oxide availability and improved fast-twitch muscle fiber efficiency [20].

In the study by Esen et al., the authors investigated whether acute supplementation with concentrated nitrate-rich beetroot juice improves intermittent exercise performance and reduces oxygen cost. Twelve recreationally active men (27 ± 10 years) consumed 140 mL of nitrate-rich beetroot juice (~12.8 mmol NO_3^-) or nitrate-depleted juice three hours before testing. After equipment calibration and a 10-minute warm-up, participants completed the Yo-Yo IR1 test while VO_2 was measured breath-by-breath, and capillary blood samples were collected. Supplementation significantly increased the distance covered in the Yo-Yo IR1 (990 ± 442 vs. 870 ± 357 m; $p = 0.007$), representing an improvement of ~14%. However, nitrate intake did not affect VO_2 at any stage of the test—at 160 m, 280 m, 440 m, or during VO_2peak (all $p > 0.05$). No differences were observed in VCO_2, ventilation, or blood lactate. These findings indicate that a single dose of nitrate improves intermittent performance, but without altering oxygen cost, suggesting mechanisms related to fast-twitch muscle function and calcium handling rather than improved running economy [21].

The study by Vilar et al. aimed to determine whether beetroot intake among participants of a 107 km ultramarathon (5600 m ascent / 4400 m descent) affects oxidative recovery and muscle damage. Thirty-two amateur ultra-endurance athletes (13 women, 19 men) were categorized based on questionnaire responses into beetroot consumers and non-consumers. Blood samples were collected pre-race, at the finish line, and 24 h and 48 h post-race and squat jump (SJ) performance was also assessed. Markers of muscle damage (CK, LDH), inflammation (CRP), antioxidant enzymes (GPx, GR), and oxidative stress (MDA, CG) were analyzed. Results showed that beetroot consumers displayed a more favorable oxidative recovery profile, including higher GPx activity at 24 and 48 h and lower increases in CK and LDH. Differences in SJ performance at the finish line also suggested less loss of muscle function. Collectively, these results indicate that beetroot consumption helps attenuate oxidative stress and muscle damage following extreme endurance exercise, thereby supporting faster recovery [22].

In the study by Balsalobre-Fernández et al., a double-blind randomized study was used with 12 elite middle- and long-distance runners who consumed either nitrate-rich beetroot juice or placebo daily for 15 days. Before and after supplementation, participants performed a treadmill test to exhaustion, during which time to exhaustion (TEx), running economy, muscle oxygenation (SmO_2), leg stiffness, and perceived exertion (RPE) were measured at 15, 17.1, and 20 km/h. The nitrate-supplemented group showed improvements in all perceptual and physiological measures: lower RPE, higher SmO_2, and longer TEx compared with placebo. These findings indicate that 15 days of nitrate supplementation enhances subjective and physiological tolerance to exercise and improves endurance performance, without altering biomechanics or running economy [23].

In the Shannon study, eight trained runners completed 1500 m and 10,000 m treadmill time trials on two occasions, each time consuming 140 mL of nitrate-rich beetroot juice or placebo three hours beforehand. Running time, VO_2, heart rate, and blood lactate were recorded. Supplementation improved performance only in the shorter trial: runners completed the 1500 m an average of ~6 seconds faster, and lactate levels were higher, indicating greater anaerobic engagement. There was no improvement in the 10 km performance nor changes in VO_2 or heart rate. These findings suggest that nitrate supplementation benefits short, high-intensity running but is ineffective for longer endurance efforts [24].

The systematic review by Esen et al. included 19 randomized crossover studies examining the effects of nitrate supplementation on muscle contractile properties during short-duration efforts (<3 min). The authors analyzed maximal strength, peak power, mean power, and time to peak power. The meta-analysis showed that nitrate supplementation does not increase maximal strength but does enhance power output and reduces the time needed to reach peak power. Although the effects were small, they were statistically significant, indicating that nitrates are most effective in activities requiring rapid generation of high power rather than maximal isometric force production [25].

In the study by Thompson et al., 36 physically active adults were assigned to one of three groups: sprint-interval training with placebo, sprint-interval training with nitrate-rich beetroot juice (~13 mmol/day), or nitrate supplementation alone without training. The intervention lasted four weeks, and participants completed exercise tests and provided blood samples and muscle biopsies. Results showed that only the nitrate-supplemented groups exhibited reduced oxygen consumption during moderate-intensity exercise. The combined training + nitrate group demonstrated the greatest increase in peak power during an incremental test and more favorable metabolic changes during high-intensity exercise—including lower lactate and higher pH. Only this group also showed a reduction in type IIx muscle fiber proportion, suggesting beneficial muscular adaptation. Importantly, improvements in time to exhaustion were similar between training groups with and without nitrate. Overall, nitrate supplementation enhanced training adaptations but did not directly improve high-intensity exercise tolerance [26].

Discussion

The analyzed studies confirm that caffeine enhances physical performance in running, regardless of its form. In sprint efforts, caffeine influences the nervous system and increases the recruitment of fast-twitch muscle fibers, resulting in greater power output and faster acceleration [7]. In long-distance running, it significantly reduces perceived fatigue, allowing athletes to maintain intensity without increasing physiological strain. In studies involving repeated high-intensity efforts, greater metabolic activation was observed, suggesting that caffeine may help sustain performance even with short recovery periods. The consistency of these findings with results from the meta-analysis further supports the conclusion that caffeine is an effective and versatile supplement for improving running performance [8]. The analyzed studies also present certain limitations, including varying supplementation protocols, small group of participants, and a predominance of male participants. This highlights the need for further research, particularly regarding sex differences, the role of caffeine habituation, and genetic variability in caffeine metabolism. Overall, caffeine is a well-established and versatile ergogenic aid that improves multiple aspects of running performance. Consuming a dose of 3–6 mg/kg approximately 60 minutes before exercise was shown to substantially enhance runners' outcomes.

Studies examining the effects of creatine on runners show that it exerts a clear ergogenic impact primarily in short-duration, high-intensity, and repeated running efforts. Both in sprinters and in repeated sprint protocols, creatine supplementation is associated with increases in mean power, better maintenance of running speed, and reduced fatigue accumulation. These outcomes align with the known mechanism of creatine, which enhances phosphocreatine availability and accelerates ATP resynthesis. Creatine may also reduce purine nucleotide degradation, helping athletes maintain high intensity even during the final repetitions of repeated efforts [11]. Moreover, creatine can attenuate the inflammatory response following intensive sprinting, which may support recovery in athletes training at high frequency [9]. The effectiveness of creatine appears to depend on the specific nature of the sport and the contribution of the phosphagen system to performance, as suggested by findings showing a less pronounced improvement in endurance parameters among long-distance runners [10]. The absence of a cumulative effect when creatine is combined with other ergogenic aids may stem from the complexity of the protocol and substantial individual variability in supplementation responses, highlighting the need for further research on interactions between creatine and other performance-enhancing strategies [12]. Creatine is a well-established supplement that enhances performance in anaerobic and repeated efforts, while its influence on prolonged aerobic exercise appears more limited and dependent on training specificity and individual characteristics.

Research on β-alanine indicates that it is most effective in supporting high-intensity efforts and repeated sprints, where rapid fatigue development is driven by the accumulation of hydrogen ions. The increased muscle carnosine content observed after supplementation enhances buffering capacity and delays muscle acidification, which translates into better tolerance of intense effort and reduced neuromuscular fatigue, as demonstrated in intervention studies using sprint and HIIT protocols [13]. In endurance-type exercise, the effects of β-alanine are more moderate—although it does not increase VO_2peak, it can extend time to exhaustion and reduce metabolic strain during submaximal workloads, suggesting improved tolerance of exercise intensity rather than enhanced aerobic capacity [14]. Differences in training protocols, β-alanine dosing, and participants' training status may explain the variability of findings. Despite this, β-alanine remains an effective and well-studied supplement that supports runners during high-intensity training and helps delay fatigue, particularly in short and repeated efforts.

The analysis of twelve studies indicates that the effects of beetroot juice, dietary nitrates, and betalains on exercise performance and recovery are highly dependent on exercise modality, athlete training status, and supplementation protocol. The most consistent ergogenic benefits of nitrate supplementation are observed during short, high-intensity, and intermittent exercise, where nitrates improve power output, time to exhaustion, and exercise tolerance [15, 20, 21, 23, 24, 25]. These improvements likely result from greater nitric oxide availability and enhanced function of fast-twitch muscle fibers, which are more responsive to nitrate supplementation [25]. A recurring theme is that highly trained athletes respond less robustly to nitrate supplementation. Individuals with lower VO_2max show substantially larger increases in plasma nitrite and clearer performance improvements than well-trained athletes [17]. This helps explain the lack of benefits observed in professional rugby players [16] and elite endurance runners [23]. In highly trained populations, natural nitric oxide production and metabolic efficiency may already be optimized, leaving little room for further enhancement. In studies involving long-duration endurance exercise, such as marathons or ultra-endurance events, nitrate supplementation rarely produced meaningful improvements in performance or recovery [18, 24]. These activities rely predominantly on slow-twitch fibers, which appear less sensitive to nitrate-mediated effects, and the degree of muscle damage in trained athletes may be too low for supplementation to demonstrate measurable recovery benefits [18]. In contrast, betalains show a different pattern of effects. Despite containing no nitrates, betalain-rich supplements improved both performance and recovery in triathletes [19] and were associated with reduced oxidative stress and muscle damage in ultra-endurance runners [22]. This suggests that beetroot's ergogenic potential extends beyond nitrate metabolism and likely involves strong antioxidant and anti-inflammatory actions. Variation in study outcomes also reflects differences in dose, duration, timing, and form of supplementation. In several studies, increases in physiological markers (e.g., plasma nitrite) did not translate into measurable performance improvements [15, 16, 21], highlighting the complexity of linking biochemical responses to functional outcomes. Overall, nitrate supplementation appears most beneficial for short, intense exercise bouts and in athletes with moderate training status, while betalain-rich products may offer broader advantages for post-exercise recovery. Future research should account for individual responsiveness to supplementation and work toward standardized protocols to improve comparability across studies [25, 26].

Conclusions

The analyzed studies show that caffeine, creatine, β-alanine, and beetroot-derived supplements each enhance running performance, but their effects are exercise-specific. Caffeine provides the most consistent benefits across sprint, repeated, and endurance running by reducing perceived effort and enhancing neuromuscular activation. Creatine is particularly effective in short and repeated high-intensity efforts, improving power output and fatigue resistance. β-alanine enhances performance mainly in high-intensity and fatigue-inducing conditions, owing to increased muscle buffering capacity. Beetroot juice and dietary nitrates improve performance primarily in short, intense, or intermittent exercise, with stronger effects in moderately trained athletes, while betalains contribute to enhanced recovery through antioxidant and anti-inflammatory actions. Overall, these supplements can be effective ergogenic aids when matched appropriately to the type of running activity and athlete characteristics.

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REFERENCES

1. Hobson, R. M., Saunders, B., Ball, G., Harris, R. C., & Sale, C. (2012). Effects of β-alanine supplementation on exercise performance: A meta-analysis. *Amino Acids, 43*(1), 25–37. https://doi.org/10.1007/s00726-011-1200-z
2. Burke, R., Piñero, A., Coleman, M., Mohan, A., Sapuppo, M., Augustin, F., Aragon, A. A., Candow, D. G., Forbes, S. C., Swinton, P., & Schoenfeld, B. J. (2023). The effects of creatine supplementation combined with resistance training on regional measures of muscle hypertrophy: A systematic review with meta-analysis. *Nutrients, 15*(9), 2116. https://doi.org/10.3390/nu15092116
3. Wylie, L. J., Kelly, J., Bailey, S. J., Blackwell, J. R., Skiba, P. F., Winyard, P. G., Jeukendrup, A. E., Vanhatalo, A., & Jones, A. M. (2013). Beetroot juice and exercise: Pharmacodynamic and dose-response relationships. *Journal of Applied Physiology, 115*(3), 325–336. https://doi.org/10.1152/japplphysiol.00372.2013
4. Barcelos, R. P., Lima, F. D., Carvalho, N. R., Bresciani, G., & Royes, L. F. (2020). Caffeine effects on systemic metabolism, oxidative-inflammatory pathways, and exercise performance. *Nutrition Research, 80*, 1–17. https://doi.org/10.1016/j.nutres.2020.05.005
5. Ping, W. C., Keong, C. C., & Bandyopadhyay, A. (2010). Effects of acute supplementation of caffeine on cardiorespiratory responses during endurance running in a hot & humid climate. *The Indian Journal of Medical Research, 132*, 36–41.
6. Matsumura, T., Tomoo, K., Sugimoto, T., Tsukamoto, H., Shinohara, Y., Otsuka, M., & Hashimoto, T. (2023). Acute effect of caffeine supplementation on 100-m sprint running performance: A field test. *Medicine & Science in Sports & Exercise, 55*(3), 525–533. https://doi.org/10.1249/MSS.0000000000003057
7. Liu, X., Huo, L., Wang, F., Wang, T., Rong, W., & He, Y. (2025). Caffeine and beetroot juice optimize 1,000-m performance: Shapley additive explanations analysis. *American Journal of Men's Health, 19*(2), 15579883251327907. https://doi.org/10.1177/15579883251327907
8. Wang, Z., Qiu, B., Gao, J., & Del Coso, J. (2022). Effects of caffeine intake on endurance running performance and time to exhaustion: A systematic review and meta-analysis. *Nutrients, 15*(1), 148. https://doi.org/10.3390/nu15010148
9. Deminice, R., Rosa, F. T., Franco, G. S., Jordao, A. A., & de Freitas, E. C. (2013). Effects of creatine supplementation on oxidative stress and inflammatory markers after repeated-sprint exercise in humans. *Nutrition, 29*(9), 1127–1132. https://doi.org/10.1016/j.nut.2013.03.003
10. Tyka, A. K., Chwastowski, M., Cison, T., Palka, T., Tyka, A., Szygula, Z., Pilch, W., Strzala, M., & Cepero, M. (2015). Effect of creatine malate supplementation on physical performance, body composition and selected hormone levels in sprinters and long-distance runners. *Acta Physiologica Hungarica, 102*(1), 114–122. https://doi.org/10.1556/APhysiol.102.2015.1.12
11. Bogdanis, G. C., Nevill, M. E., Aphamis, G., Stavrinou, P. S., Jenkins, D. G., Giannaki, C. D., Lakomy, H. K. A., & Williams, C. (2022). Effects of oral creatine supplementation on power output during repeated treadmill sprinting. *Nutrients, 14*(6), 1140. https://doi.org/10.3390/nu14061140
12. Huerta Ojeda, Á., & Jorquera-Aguilera, C. (2024). Combined impact of creatine, caffeine, and variable resistance on repeated sprint ability in young soccer players. *Nutrients, 16*(15), 2437. https://doi.org/10.3390/nu16152437
13. Milioni, F., de Poli, R. A. B., Saunders, B., Gualano, B., da Rocha, A. L., Sanchez Ramos da Silva, A., Muller, P. T. G., & Zagatto, A. M. (2019). Effect of β-alanine supplementation during high-intensity interval training on repeated sprint ability performance and neuromuscular fatigue. *Journal of Applied Physiology, 127*(6), 1599–1610. https://doi.org/10.1152/japplphysiol.00321.2019
14. Marko, D., Snarr, R. L., Bahenský, P., Bunc, V., Krajcigr, M., & Malý, T. (2025). Beta-alanine supplementation improves time to exhaustion, but not aerobic capacity, in competitive middle- and long-distance runners. *Journal of the International Society of Sports Nutrition, 22*(1), 2521336. https://doi.org/10.1080/15502783.2025.2521336
15. Lansley, K. E., Winyard, P. G., Fulford, J., Vanhatalo, A., Bailey, S. J., Blackwell, J. R., DiMenna, F. J., Gilchrist, M., Benjamin, N., & Jones, A. M. (2011). Dietary nitrate supplementation reduces the O2 cost of walking and running: A placebo-controlled study. *Journal of Applied Physiology, 110*(3), 591–600. https://doi.org/10.1152/japplphysiol.01070.2010
16. Esen, O., Karayigit, R., & Peart, D. J. (2023). Acute beetroot juice supplementation did not enhance intermittent running performance in trained rugby players. *European Journal of Sport Science, 23*(12), 2321–2328. https://doi.org/10.1080/17461391.2023.2230942
17. Porcelli, S., Ramaglia, M., Bellistri, G., Pavei, G., Pugliese, L., Montorsi, M., Rasica, L., & Marzorati, M. (2015). Aerobic fitness affects the exercise performance responses to nitrate supplementation. *Medicine & Science in Sports & Exercise, 47*(8), 1643–1651. https://doi.org/10.1249/MSS.0000000000000577
18. Clifford, T., Allerton, D. M., Brown, M. A., Harper, L., Horsburgh, S., Keane, K. M., Stevenson, E. J., & Howatson, G. (2017). Minimal muscle damage after a marathon and no influence of beetroot juice on inflammation and recovery. *Applied Physiology, Nutrition, and Metabolism, 42*(3), 263–270. https://doi.org/10.1139/apnm-2016-0525

19. Montenegro, C. F., Kwong, D. A., Minow, Z. A., Davis, B. A., Lozada, C. F., & Casazza, G. A. (2017). Betalain-rich concentrate supplementation improves exercise performance and recovery in competitive triathletes. *Applied Physiology, Nutrition, and Metabolism, 42*(2), 166–172. https://doi.org/10.1139/apnm-2016-0452
20. Nyakayiru, J., Jonvik, K. L., Trommelen, J., Pinckaers, P. J., Senden, J. M., van Loon, L. J., & Verdijk, L. B. (2017). Beetroot juice supplementation improves high-intensity intermittent type exercise performance in trained soccer players. *Nutrients, 9*(3), 314. https://doi.org/10.3390/nu9030314
21. Esen, O., Domínguez, R., & Karayigit, R. (2022). Acute beetroot juice supplementation enhances intermittent running performance but does not reduce oxygen cost of exercise among recreational adults. *Nutrients, 14*(14), 2839. https://doi.org/10.3390/nu14142839
22. Vilar, E., Collado-Boira, E., Guerrero, C., Folch-Ayora, A., Salas-Medina, P., Hernando, C., Baliño, P., & Muriach, M. (2024). Is there a role of beetroot consumption on the recovery of oxidative status and muscle damage in ultra-endurance runners? *Nutrients, 16*(5), 583. https://doi.org/10.3390/nu16050583
23. Balsalobre-Fernández, C., Romero-Moraleda, B., Cupeiro, R., Peinado, A. B., Butragueño, J., & Benito, P. J. (2018). The effects of beetroot juice supplementation on exercise economy, rating of perceived exertion and running mechanics in elite distance runners: A double-blinded, randomized study. *PLOS ONE, 13*(7), e0200517. https://doi.org/10.1371/journal.pone.0200517
24. Shannon, O. M., Barlow, M. J., Duckworth, L., Williams, E., Wort, G., Woods, D., Siervo, M., & O'Hara, J. P. (2017). Dietary nitrate supplementation enhances short but not longer duration running time-trial performance. *European Journal of Applied Physiology, 117*(4), 775–785. https://doi.org/10.1007/s00421-017-3580-6
25. Esen, O., Dobbin, N., & Callaghan, M. J. (2023). The effect of dietary nitrate on the contractile properties of human skeletal muscle: A systematic review and meta-analysis. *Journal of the American Nutrition Association, 42*(4), 327–338. https://doi.org/10.1080/07315724.2022.2037475
26. Thompson, C., Wylie, L. J., Blackwell, J. R., Fulford, J., Black, M. I., Kelly, J., McDonagh, S. T., Carter, J., Bailey, S. J., Vanhatalo, A., & Jones, A. M. (2017). Influence of dietary nitrate supplementation on physiological and muscle metabolic adaptations to sprint interval training. *Journal of Applied Physiology, 122*(3), 642–652. https://doi.org/10.1152/japplphysiol.00909.2016