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Sports Nutrition Strategies for Optimizing Performance, Recovery, and Immune Function in Endurance Athletes: A Review of Key Ergogenic Supplements

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Abstract

This review examines the role of targeted sports nutrition in addressing the primary physiological challenges faced by endurance athletes, including dehydration, muscle glycogen depletion, and exercise-induced immunosuppression. While a foundation of whole foods and proper training is essential, the demands of high-volume or high-intensity exercise often necessitate strategic supplementation. The paper analyzes the efficacy and practical application of several categories of ergogenic aids. These include macronutrient-based supplements (carbohydrates, proteins, and their optimal 4:1 ratio for pre-, during, and post-exercise timing), as well as specific compounds like phosphate salts, branched-chain amino acids (BCAAs), caffeine, ephedrine, glycerol, and creatine. Furthermore, the review highlights the importance of nutritional support for the immune system, evaluating evidence for bovine colostrum, glutamine, and zinc in mitigating the risks of overtraining syndrome and infection. Finally, the abstract touches upon the legal and ethical considerations for supplement use in competitive sport. The synthesis of current evidence provides practical guidelines for timing, dosage, and nutrient combinations to enhance endurance capacity, accelerate recovery, and maintain health, concluding that a well-planned sports nutrition regimen is a cornerstone of successful endurance performance.

Keywords

• Endurance performance • Ergogenic aids • Sports nutrition • Glycogen resynthesis • Immune function • Supplementation timing • Carbohydrate-protein ratio • Overtraining syndrome

1. Introduction

The nutritional demands placed upon endurance athletes far exceed those of sedentary individuals, necessitating a comprehensive approach to dietary planning that integrates both whole foods and strategic supplementation. Success in endurance sports requires not only rigorous physical preparation but also a meticulous nutritional strategy that addresses the body's heightened requirements for energy substrates, fluid balance, and tissue repair. The relationship between dietary intake and athletic performance has been extensively documented, with research demonstrating that even minor nutritional deficiencies can significantly impair training adaptations and competitive outcomes [1]. These considerations become increasingly critical during periods of high-volume training or competition, where the body's homeostatic mechanisms are subjected to sustained physiological stress.

Understanding the factors that limit endurance performance provides the foundation for developing effective nutritional interventions. The primary physiological challenges faced by endurance athletes include the progressive depletion of muscle glycogen stores, the decline in blood glucose availability, and

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the gradual onset of dehydration, all of which contribute to the phenomenon of fatigue. The cardiovascular drift, characterized by a progressive increase in heart rate and decrease in stroke volume during prolonged exercise, represents the body's compensatory response to the redistribution of blood volume. This physiological adaptation, while beneficial for thermoregulation, ultimately limits the athlete's capacity to sustain high-intensity output. The magnitude of these challenges is particularly evident during exercise in hot and humid conditions, where the rate of fluid loss through sweating can reach levels that compromise cardiovascular function and thermoregulatory capacity.

The strategic application of nutritional supplements offers a practical means of mitigating these performance-limiting factors, providing athletes with additional tools to support training adaptations and competitive performance. The use of supplements in sports nutrition has evolved significantly over recent decades, moving from anecdotal practices toward evidence-based interventions supported by rigorous scientific investigation. The current body of research provides substantial support for the efficacy of specific supplements, including carbohydrates, proteins, and various ergogenic compounds, when employed within the framework of a well-designed nutritional strategy. The timing of nutrient ingestion, the selection of appropriate carbohydrate sources based on glycemic index considerations, and the integration of protein supplementation to enhance recovery have all emerged as critical components of effective sports nutrition protocols.

The role of nutritional support extends beyond immediate performance enhancement to encompass the maintenance of immune function during periods of intense training. Endurance athletes engaged in high-volume training are particularly susceptible to transient immunosuppression, which can manifest as increased susceptibility to upper respiratory tract infections and other illnesses. The relationship between training load and immune function represents a significant area of research, with evidence suggesting that strategically timed nutritional interventions can help maintain immune competence [2]. The application of specific nutritional compounds, including bovine colostrum, glutamine, and zinc, has shown promise in supporting immune function and reducing the incidence of illness during periods of intensified training.

The regulatory and ethical landscape surrounding supplement use in sport presents additional considerations for athletes and their support teams. The legal status of specific compounds varies across sporting organizations and jurisdictions, requiring careful attention to compliance with anti-doping regulations. The ethical dimension of supplementation extends beyond legality to encompass considerations of fair competition and the integrity of athletic achievement. Athletes must navigate these complex considerations while making informed decisions about the incorporation of supplements into their nutritional protocols.

2. Methodology / Search Strategy

This review was conducted as a narrative review with a structured search strategy, designed to identify, evaluate, and synthesize the evidence on nutritional strategies and ergogenic supplements for endurance athletes. The methodology is reported here to make the selection of studies transparent and to clarify the scope of the evidence discussed in Sections 3–8.

2.1 Databases Searched

Searches were conducted in PubMed/MEDLINE, Scopus, and Web of Science. Reference lists of included reviews and position stands were hand-searched to identify additional relevant trials (backward citation searching), and forward citation searching was performed for key position stands and meta-analyses.

2.2 Search Terms

The search strategy combined three concept blocks using Boolean operators:

- **Population/context:** "endurance athlete" OR "endurance exercise" OR "endurance performance" OR "cyclist" OR "runner" OR "triathlete" OR "prolonged exercise."
- **Intervention:** "sports nutrition" OR "ergogenic aid" OR "supplement" OR "carbohydrate" OR "protein" OR "caffeine" OR "creatine" OR "branched-chain amino acid" OR "BCAA" OR "phosphate" OR "glycerol" OR "ephedrine" OR "colostrum" OR "glutamine" OR "zinc."
- **Outcome:** "performance" OR "recovery" OR "glycogen resynthesis" OR "immune function" OR "upper respiratory tract infection" OR "fatigue" OR "time to exhaustion."

Terms within each block were combined with OR, and the three blocks were combined with AND. Search strings were adapted to the syntax of each database.

2.3 Inclusion and Exclusion Criteria

Inclusion criteria:

- Randomized controlled trials, systematic reviews, meta-analyses, and position stands addressing nutritional or ergogenic supplementation in endurance or mixed-sport contexts;
- Studies reporting performance, recovery, hydration, or immune-function outcomes;
- Human studies published in peer-reviewed journals in English.

Exclusion criteria:

- Animal studies and in vitro studies without human outcome data;
- Case reports, conference abstracts, and unpublished theses;
- Studies in which the supplement was co-administered with other agents such that the independent effect could not be isolated, unless the combination itself was the object of review;
- Studies not reporting a relevant outcome or not providing sufficient methodological detail for appraisal.

2.4 Evidence Appraisal and Synthesis

Because the included literature is heterogeneous in dose, formulation, participant training status, and outcome measurement, findings were synthesized narratively rather than pooled quantitatively. Each supplement category was graded using the framework defined in Table 1 (Strong, Moderate, Mixed), reflecting the consistency of findings across randomized controlled trials and the availability of position-stand or meta-analytic support. This grading framework is applied consistently in Sections 7–8 and in Table 1.

3. Related Work

The scientific literature on sports nutrition and ergogenic supplementation has expanded considerably over the past decade, with numerous reviews and meta-analyses synthesizing evidence across various supplement categories. Wiącek and Karolkiewicz examined the distinct nutritional approaches required for sports with different metabolic characteristics, highlighting how endurance athletes benefit from high-carbohydrate diets and buffering agents such as sodium bicarbonate and beta-alanine, while anaerobic athletes require different strategies altogether. This foundational work established the principle that supplement efficacy is context-dependent and must be matched to the specific metabolic demands of the sport.

The ergogenic effects of supplement combinations on endurance performance have been systematically evaluated by Zart and Fröhlich, who conducted a comprehensive meta-analysis of randomized controlled trials examining various supplement combinations [1]. Their findings indicated that while individual supplements like caffeine and sodium bicarbonate demonstrate ergogenic effects, the evidence for combined supplementation remains less conclusive, suggesting that additive or synergistic benefits cannot be assumed. This work highlights the importance of rigorous evaluation of supplement protocols rather than relying on anecdotal or theoretical benefits.

Beyond these foundational reviews, several position stands and meta-analyses provide the evidentiary scaffolding for the supplement categories discussed in this paper. The American College of Sports Medicine, Dietitians of Canada, and the Academy of Nutrition and Dietetics jointly position carbohydrate availability as the principal nutritional determinant of endurance performance, recommending 6–10 $\mathrm{g{\cdot}kg^{-1}{\cdot}day^{-1}}$ for daily training and higher intakes during carbohydrate loading [3]. The International Society of Sports Nutrition similarly endorses protein intakes of 1.4–2.0 $\mathrm{g{\cdot}kg^{-1}{\cdot}day^{-1}}$ for exercising individuals, a range that informs the protein component of the 4:1 carbohydrate–protein formulations discussed in Sections 6 and 7 [4]. Jeukendrup's multiple-transportable carbohydrate framework has reframed in-exercise feeding by demonstrating that glucose–fructose co-ingestion can raise exogenous carbohydrate oxidation to approximately 1.0–1.1 $\mathrm{g{\cdot}min^{-1}}$, exceeding the ceiling observed with glucose alone [5].

Conflicting findings across the literature are not uniformly resolved. Whereas Burke et al. conclude that carbohydrate mouth rinsing and low-to-moderate glycemic index pre-exercise meals confer modest but reproducible benefits, other trials report null effects when total carbohydrate intake is controlled [6]. For caffeine, the International Society of Sports Nutrition position stand supports ergogenic effects at 3–6 $\mathrm{mg{\cdot}kg^{-1}}$ across endurance, strength, and team-sport contexts [7], yet Zart and Fröhlich's meta-analysis of supplement combinations cautions that additive effects of caffeine with other agents are not consistently reproduced [1]. The creatine literature shows a similar pattern: Kreider et al. document strong evidence for strength and repeated-sprint outcomes but weaker and more context-dependent evidence for continuous endurance performance [8], consistent with the scoping review by Wesołowski et al. that reports heterogeneous effects in mixed-sport contexts. Finally, the immune-support literature remains split between studies reporting reduced upper respiratory tract infection incidence with colostrum [2, 9] and reviews finding insufficient evidence for glutamine and zinc prophylaxis at typical supplemental doses [10, 11]. This review therefore treats the evidence for each category as graded rather than uniform, and the practical recommendations in Section 9 are qualified accordingly.

4. Factors Limiting Endurance Performance and the Role of Nutrition

The depletion of muscle glycogen stores represents one of the most significant factors limiting endurance performance, particularly during sustained exercise at moderate to high intensities. Muscle glycogen serves as the primary substrate for energy production during prolonged physical activity, with its availability directly influencing the duration and intensity of exercise that can be maintained. The relationship between pre-exercise muscle glycogen concentration and time to exhaustion has been well-established, with higher initial glycogen levels correlating with improved endurance capacity. The rate of glycogen utilization is determined by the intensity of exercise, with higher intensities resulting in more rapid glycogen depletion and an accelerated onset of fatigue.

The progressive decline in blood glucose availability represents another critical factor that contributes to the onset of fatigue during endurance exercise. As glycogen stores become depleted, the body increasingly relies on blood glucose as a fuel source for both the working muscles and the central nervous system. When hepatic glucose production cannot keep pace with peripheral glucose utilization, hypoglycemia ensues, leading to impairments in both physical and cognitive function. The integration of carbohydrate supplementation during prolonged exercise serves to maintain blood glucose levels and preserve muscle glycogen, thereby extending endurance capacity [1]. Research has demonstrated that carbohydrate intake at rates of 45 to 60 grams per hour can significantly delay the onset of fatigue by maintaining glucose availability and reducing the rate of glycogen depletion [3, 5, 6].

The maintenance of fluid balance represents another critical consideration for endurance performance, with even modest levels of dehydration producing measurable impairments in cardiovascular function and thermoregulatory capacity. The cardiovascular drift phenomenon, characterized by a progressive increase in heart rate and decrease in stroke volume during prolonged exercise, results from the redistribution of blood volume toward the periphery for thermoregulatory purposes. This physiological adaptation, while beneficial for heat dissipation, ultimately limits the athlete's ability to sustain cardiac output at high exercise intensities. The loss of body fluid equivalent to one percent of body weight can significantly reduce blood volume, placing increased strain on the cardiovascular system and limiting athletic performance [12]. More severe dehydration, exceeding four percent of body weight, can result in heat exhaustion and potentially life-threatening conditions such as heat stroke.

5. Strategies for Pre-exercise Nutrition and Supplementation

The objectives of pre-exercise nutrition extend beyond simple energy provision to encompass the optimization of training adaptations, the enhancement of recovery capacity, and the prevention of exercise-induced catabolism. The selection of appropriate carbohydrate sources based on glycemic index considerations plays a critical role in supporting sustained energy availability during prolonged exercise. Low-to-moderate glycemic index foods provide a slow, sustained release of glucose into the bloodstream, which may be particularly beneficial during exercise sessions that extend beyond 90 minutes in duration. The consumption of carbohydrates with lower glycemic index values can help maintain stable blood glucose levels and reduce the risk of premature hypoglycemia during prolonged exercise.

The timing of nutrient consumption relative to exercise sessions is essential for optimizing substrate availability and maximizing performance. The process of glycogen resynthesis requires approximately four hours for the complete storage of ingested carbohydrates in the liver and muscles. Consequently, pre-exercise meals should be consumed approximately four to six hours prior to the commencement of exercise to ensure adequate glycogen replenishment. For athletes who train in the afternoon, breakfast

represents the critical meal for topping up glycogen stores, whereas athletes who train in the morning should emphasize their evening meal for this purpose. The consumption of a light carbohydrate-protein snack 30 to 60 minutes prior to exercise can further enhance carbohydrate availability toward the end of intense exercise sessions by promoting a modest increase in glucose and insulin levels.

The integration of protein with pre-exercise carbohydrate intake offers additional benefits beyond those provided by carbohydrate consumption alone. The inclusion of protein in a pre-exercise snack can increase amino acid availability and reduce exercise-induced protein catabolism, thereby supporting muscle protein balance during and after exercise [3, 4]. Insulin, which is released in response to carbohydrate and protein intake, plays a key role in inhibiting protein degradation and promoting nitrogen retention. The anabolic effects of insulin appear to be mediated through its nitrogen-sparing properties and its promotion of amino acid uptake into tissues. The combination of carbohydrate and protein in pre-exercise nutrition may therefore provide complementary benefits for performance and recovery.

The concept of glycogen supercompensation, or carbohydrate loading, represents a strategy for maximizing pre-exercise glycogen stores in anticipation of prolonged endurance events. Traditional carbohydrate loading protocols involve several days of high carbohydrate intake following a period of glycogen depletion, although more recent research has demonstrated that simply increasing carbohydrate intake while tapering training can achieve similar results. The objective of these strategies is to increase muscle glycogen concentrations above normal resting levels, providing an enhanced substrate reserve for competition. The practical implementation of glycogen supercompensation requires attention to individual tolerance and gastrointestinal comfort, as the consumption of large quantities of carbohydrate can produce gastrointestinal distress in some athletes.

The selection of appropriate pre-exercise supplements requires consideration of individual tolerance, practical feasibility, and evidence for efficacy. Athletes should experiment with supplement protocols during training rather than attempting new approaches for the first time in competition. The role of pre-exercise nutrition extends beyond performance enhancement to include considerations of gastrointestinal comfort and psychological readiness. The establishment of reliable pre-exercise routines that include familiar foods and supplements contributes to the development of consistent performance patterns and reduces anxiety associated with competition.

The metabolic response to pre-exercise nutrition varies based on several factors, including the type and amount of nutrients consumed, the timing of consumption, and individual metabolic characteristics. Athletes with higher training volumes and intensities may benefit from more aggressive pre-exercise feeding strategies, while those with lower energy requirements may find that smaller pre-exercise feedings are sufficient. The monitoring of individual responses to different pre-exercise feeding protocols can help athletes identify optimal approaches for specific training and competition scenarios.

The practical application of the glycemic index concept in pre-exercise nutrition has implications for supplement selection and meal planning. While high-glycemic index carbohydrates can provide a rapid source of energy, low-to-moderate glycemic index foods may offer more sustained fuel availability [2]. The glycemic index is most useful for evaluating single foods or individually packaged supplements, where the ingredient composition is standardized and predictable. For whole foods and mixed meals, the interaction between different food components can alter the glycemic response, making the glycemic index a less reliable guide.

6. In-Exercise Nutrition and Recovery Supplementation

The provision of nutritional support during prolonged exercise sessions is essential for maintaining performance intensity and delaying the onset of fatigue. For exercise sessions lasting 60 to 90 minutes or longer, the availability of exogenous carbohydrates becomes increasingly important for sustaining carbohydrate oxidation rates and preserving endogenous glycogen stores. The beneficial effects of carbohydrate supplementation during exercise have been consistently demonstrated across a range of endurance activities, with athletes able to maintain higher power outputs and exercise for longer durations when consuming carbohydrates [1]. The ideal rate of carbohydrate ingestion during exercise ranges from 45 to 60 grams per hour, with higher rates potentially offering additional benefits when multiple transportable carbohydrates are utilized. More recent endurance nutrition research has refined this approach by emphasizing multiple-transportable carbohydrate formulations [5, 6]. When glucose and fructose are co-ingested, they are absorbed via separate intestinal transporters (SGLT1 and GLUT5), which can increase total carbohydrate oxidation and reduce gastrointestinal distress at higher intake rates. Commonly studied glucose-to-fructose ratios include 2:1 and 1:0.8, with the latter allowing carbohydrate delivery rates approaching 90 to 120 grams per hour in well-trained athletes who tolerate such intakes. These strategies do not replace the general 45 to 60 grams per hour recommendation for shorter or lower-intensity sessions, but they extend the upper range for prolonged, high-intensity endurance events when gastric comfort and individual tolerance are established.

The form in which carbohydrates are consumed during exercise has implications for both performance and gastrointestinal comfort. Liquid carbohydrate-electrolyte solutions offer the advantages of simultaneous fluid and fuel delivery, facilitating both hydration and substrate availability. Concentrated carbohydrate solutions exceeding 10 percent carbohydrate can delay gastric emptying and compromise fluid delivery, particularly during high-intensity exercise when gastrointestinal blood flow is reduced [12]. The selection of appropriate carbohydrate concentrations should consider the specific demands of the activity and the practical constraints of ingestion. Cyclists, who typically have greater fluid tolerance, may consume up to 1000 milliliters per hour, whereas runners often consume smaller volumes and may require more concentrated solutions to achieve adequate carbohydrate intake.

The addition of protein to in-exercise carbohydrate supplementation has emerged as a strategy for enhancing recovery and reducing muscle damage. A carbohydrate-to-protein ratio of approximately 4:1 has been used in many studies to enhance insulin secretion and promote glucose and amino acid uptake into muscle tissue, but the benefit is not universal: it depends on total carbohydrate intake, the athlete's protein requirement, and whether recovery is constrained by time or by gastrointestinal tolerance [3, 4]. The insulin-mediated effects of carbohydrate-protein supplementation may help to reduce exercise-induced cortisol secretion and minimize protein degradation. Evidence suggests that carbohydrate-protein beverages can improve time-to-exhaustion and reduce markers of muscle damage compared to carbohydrate-only formulations, although careful interpretation of the literature is required as differences in total caloric content may contribute to these effects.

The timing of in-exercise supplementation plays a critical role in optimizing the metabolic response. Regular feeding intervals of 15 to 20 minutes help maintain stable blood glucose levels and provide a continuous supply of substrate to working muscles. The proactive consumption of carbohydrates, rather than waiting until fatigue begins to develop, allows athletes to prevent the decline in blood glucose and glycogen availability that precedes the onset of fatigue. The integration of in-exercise nutrition with pre-exercise feeding strategies creates a comprehensive approach to fuel availability that supports sustained performance intensity.

The post-exercise recovery period represents a critical window for nutritional intervention, with the timing and composition of the post-exercise meal directly influencing the rate of glycogen resynthesis and muscle protein repair. The activation of glycogen synthase following exercise-induced glycogen depletion creates an opportunity for enhanced storage of glycogen, provided adequate carbohydrate is available. The consumption of carbohydrate immediately following exercise results in more rapid glycogen resynthesis compared to delayed intake, with the first two hours post-exercise representing the period of highest glycogen synthetic rate. The continued provision of carbohydrate at regular intervals during the recovery period can sustain elevated glycogen synthesis rates and promote full restoration of stores within 24 hours.

The integration of protein with post-exercise carbohydrate intake provides synergistic benefits for recovery, enhancing both glycogen resynthesis and muscle protein synthesis. The addition of protein to a carbohydrate supplement increases the insulin response, promoting the uptake of both glucose and amino acids into muscle tissue. This anabolic environment accelerates recovery and may reduce the duration of the catabolic state that follows intense exercise. The metabolic benefits of carbohydrate-protein supplementation are likely the result of the combined effects of enhanced substrate availability, elevated insulin levels, and the provision of amino acids for protein synthesis.

The practical application of recovery nutrition requires consideration of the athlete's training schedule and the demands of subsequent training sessions. For athletes with multiple training sessions on the same day, rapid glycogen resynthesis becomes essential for maintaining performance quality in the second session. The consumption of high-glycemic index carbohydrates and protein immediately after the first session, followed by regular feedings of similar composition throughout the recovery period, can accelerate glycogen resynthesis and promote muscle repair.

7. Ergogenic Supplements and Immune System Support

The pharmacological category of ergogenic supplements includes compounds that enhance physical performance by acting on the central nervous system or altering metabolic processes related to energy production. Caffeine has demonstrated consistent ergogenic effects across multiple studies, primarily through its stimulation of the central nervous system and its effects on fatty acid mobilization and glycogen sparing. The consumption of caffeine prior to exercise has been associated with increased time to exhaustion and improved performance in time-trial settings. The recommended dosage of caffeine for ergogenic benefit ranges from 3 to 6 milligrams per kilogram of body weight, although athletes should be aware of the potential for gastrointestinal distress and central nervous system side effects at higher doses [1, 7].

The inclusion of ephedrine in combination with caffeine has produced ergogenic effects in several studies, with the combination of these two compounds showing greater performance enhancement than either compound alone [1, 13]. The stimulatory effects of ephedrine on the sympathetic nervous system, combined with its metabolic effects, contribute to increased fat oxidation and glycogen sparing during exercise. These potential benefits must, however, be weighed against a well-documented safety profile: ephedrine raises heart rate and blood pressure, increases the risk of cardiac arrhythmias and adverse cardiovascular events, and has been associated with serious events including stroke and myocardial infarction, particularly when combined with caffeine or other stimulants and when used in hot environments or at high doses [13]. Ephedrine is classified as a prohibited substance in competition by the World Anti-Doping Agency, and its use for performance enhancement is therefore both a health risk and a potential anti-doping violation. Athletes should be aware of the regulatory status of ephedrine, should not use it without medical supervision, and should exercise particular caution given the cardiovascular risks

outlined above.

The branched-chain amino acids (BCAAs) have been investigated primarily for their potential to attenuate central fatigue during prolonged exercise, rather than for a direct ergogenic effect on muscle energetics. The central fatigue hypothesis proposes that exercise-induced increases in free tryptophan availability, relative to BCAA competition at the large neutral amino acid transporter, elevate brain serotonin synthesis and contribute to fatigue [14]. Under this mechanism, BCAA ingestion during exercise would be expected to lower the tryptophan-to-BCAA ratio and limit serotonin accumulation. The empirical support for this pathway is, however, limited and inconsistent: several small trials report reduced perceived exertion or improved time to exhaustion with BCAA ingestion, whereas others find no effect on endurance performance when energy intake and total protein are controlled [1, 14]. Importantly, the doses used in positive trials are frequently large (often 10–20 g), and the marginal benefit relative to carbohydrate–electrolyte intake alone is small. The evidence for BCAA supplementation in recovery is similarly equivocal, with proposed reductions in muscle soreness and markers of muscle damage not consistently replicated. On current evidence, BCAAs should therefore be regarded as a supplement with mixed and context-dependent effects rather than a routine ergogenic aid, and their use should not displace adequate total protein intake, which remains the primary nutritional strategy for supporting recovery [4].

The use of phosphate salts as an ergogenic supplement has been supported by research demonstrating enhanced oxygen delivery and improved exercise performance. Phosphate salts may act by increasing 2,3-diphosphoglycerate concentrations in red blood cells, facilitating oxygen release to tissues and improving aerobic capacity [15]. Studies have shown improvements in maximal oxygen uptake and anaerobic threshold following phosphate loading, suggesting increased metabolic efficiency. The mechanisms underlying the ergogenic effects of phosphate supplementation remain incompletely understood, and more research is needed to confirm the efficacy and safety of this approach.

The physiological ergogenic category includes substances that augment natural physiological processes, such as glycerol and creatine. Glycerol supplementation, when combined with water, has been shown to increase plasma volume and tissue hydration, potentially delaying the onset of dehydration during exercise in hot environments [12, 16]. The hyperhydration effects of glycerol can reduce heart rate and core temperature during exercise, extending endurance capacity when training in the heat. The dosing of glycerol at 1 gram per kilogram of body weight has been used in research, although athletes should be aware of potential gastrointestinal side effects at these doses.

Creatine supplementation has emerged as a performance enhancer not only for strength and power athletes but also for endurance athletes participating in intermittent, high-intensity activities. Creatine loading protocols, typically involving 20 to 30 grams per day for five to seven days, have been shown to increase muscle creatine phosphate content, enhancing ATP resynthesis and buffering capacity [8]. Research has demonstrated that creatine supplementation can improve repeated sprint performance and delay the onset of fatigue in activities requiring repeated high-intensity efforts interspersed with recovery periods. The secondary benefits of creatine for endurance athletes may include improvements in anaerobic threshold and reductions in blood lactate accumulation during high-intensity exercise.

The support of immune function through nutritional supplementation represents a growing area of sports nutrition research, with several compounds showing promise for mitigating the immunosuppressive effects of intense training. Bovine colostrum supplementation has been associated with improved immune function and reduced markers of muscle damage in studies of athletes engaged in heavy training [2, 9]. The immunoglobulins and growth factors present in colostrum may contribute to enhanced mucosal immunity and reduced incidence of upper respiratory tract infections. Glutamine supplementation has also been investigated for its immune-supporting properties, on the rationale that glutamine is an

important fuel for lymphocytes and may become conditionally limiting during periods of metabolic stress; however, controlled trials in endurance athletes have not consistently demonstrated reductions in infection incidence, and the evidence base remains insufficient to recommend glutamine as a routine prophylactic [10, 17]. Zinc supplementation has a well-established role in immune function, and endurance athletes may experience small zinc losses through sweating; nevertheless, the evidence that zinc supplementation prevents exercise-induced upper respiratory tract infections is limited and inconsistent, and chronic high-dose supplementation carries risks of copper deficiency and impaired immune function [11]. Zinc should therefore be considered only where a deficiency is documented or suspected, rather than as a general immune prophylactic.

8. Integrating Nutritional Supplements for Performance: Practical Considerations

The practical application of sports nutrition principles requires athletes to develop individualized protocols that account for their training demands, competition schedules, and physiological responses. The integration of pre-, during-, and post-exercise nutrition creates a comprehensive approach that supports performance, recovery, and immune function. The following guidelines represent a synthesis of current evidence for the optimization of sports nutrition practice, with recommendations applicable to most endurance athletes across various disciplines.

For pre-exercise preparation, athletes should prioritize glycogen supercompensation through carbohydrate intake of 7 to 10 grams per kilogram of body weight daily during taper periods, a range consistent with position-stand recommendations for pre-event carbohydrate loading [3, 6]. Hyperhydration should be achieved through regular fluid intake during the days preceding competition, ensuring full hydration status [12, 16]. The consumption of 500 to 1000 milliliters of fluid prior to exercise, along with 200 to 300 grams of carbohydrate when in-exercise supplementation may be limited, supports energy availability and reduces the risk of premature fatigue [3]. The selection of familiar, well-tolerated food and supplement options reduces the risk of gastrointestinal distress and contributes to psychological preparation for competition.

During exercise, athletes should aim to replace all fluid losses, although practical constraints may make this challenging in hot and humid conditions. Frequent small volumes of fluid, 150 to 250 milliliters every 15 minutes, are better tolerated than larger volumes consumed less frequently [1, 16]. The consumption of 45 to 60 grams of high-glycemic index carbohydrates per hour supports carbohydrate oxidation rates and preserves muscle glycogen, and higher intakes of up to 90 grams per hour may be appropriate when multiple transportable carbohydrates are used and tolerated [5, 6]. Carbohydrate solutions should not exceed 10 percent concentration when hydration is a primary concern [3]. Electrolyte replacement, particularly sodium and potassium, should be considered, with most commercial sports drinks providing appropriate electrolyte content. For athletes who require additional electrolyte support, electrolyte tablets or supplements may be considered.

The incorporation of protein into in-exercise supplementation at a 4:1 carbohydrate-to-protein ratio may enhance performance and reduce muscle damage. Protein addition can be particularly beneficial during exercise sessions lasting more than two hours or when training in hot environments where caloric requirements are elevated. For athletes who prefer solid foods, energy bars and gels provide convenient alternatives to liquid supplements, with comparable metabolic effects when thermal stress is not a factor. The selection of supplements should be guided by individual preference, gastrointestinal tolerance, and evidence for efficacy.

The post-exercise recovery period requires prompt nutritional intervention to maximize glycogen

resynthesis and promote muscle repair. Rapid rehydration requires early fluid consumption, replacing at least 150 percent of fluid losses with dilute sodium-containing solutions [16]. The recommended carbohydrate intake for glycogen resynthesis varies based on the training demands of the subsequent period, ranging from 5 to 7 grams per kilogram for moderate training to 10 to 12 grams per kilogram for extreme training volumes, consistent with current position-stand guidance [3, 6]. When rapid recovery is required, carbohydrate intake of 1.0 to 1.2 grams per kilogram per hour should be consumed at frequent intervals, starting within the first 30 minutes post-exercise [6].

The addition of protein to post-exercise carbohydrate supplementation enhances glycogen resynthesis when carbohydrate intake is suboptimal or when frequent supplementation is not possible. A 4:1 carbohydrate-to-protein ratio is one commonly studied formulation that can provide an anabolic stimulus, reducing muscle damage and stimulating protein accretion, provided total carbohydrate intake remains adequate for the required rate of glycogen resynthesis [3, 4]. Post-exercise carbohydrate-protein supplements may also support immune function, reducing the risk of exercise-induced immunosuppression that can occur during periods of intense training. The inclusion of bovine colostrum may be beneficial during periods of heavy training or for athletes with a history of illness during intense training blocks, as it shows moderate promise for immune support [2, 9]; by contrast, glutamine and zinc are not supported as routine prophylactics unless a specific deficiency is present [10, 11, 17].

Athletes should consider the use of pharmacological and physiological ergogenic aids based on individual goals and the specific demands of their sport. Caffeine, branched-chain amino acids, phosphate salts, and creatine have all been shown to provide performance benefits for endurance athletes under specific conditions. However, athletes must be aware of the regulatory status of these compounds, as some are prohibited by sporting organizations and may result in doping violations if used inappropriately. The ethical dimension of supplement use requires athletes to consider whether their use aligns with their personal values and the principles of fair competition.

The effectiveness of any nutritional supplement depends on its integration into a comprehensive training and nutrition strategy. Supplements should not be viewed as replacements for sound nutritional practices, but rather as adjuncts that can provide additional benefits when used appropriately. Athletes should work with qualified sports nutrition professionals to develop personalized protocols that account for individual metabolic characteristics, training goals, and practical considerations. The monitoring of individual responses to nutritional interventions helps identify optimal approaches and enables adjustments based on evolving training demands.

9. Discussion and Legal-Ethical Considerations

The synthesis of current research on nutritional supplements for endurance athletes reveals substantial evidence for the efficacy of several compounds when incorporated into a comprehensive sports nutrition strategy. As detailed in Sections 6–8, the proposed mechanisms for these benefits include enhanced substrate availability, reduced muscle protein breakdown, and improved immune function during periods of intense training. Rather than restating the compound-specific evidence, this discussion focuses on the interpretive and regulatory issues that condition its practical implementation. In particular, the potential for placebo effects and other confounding variables requires careful interpretation of the existing literature, particularly when considering the practical implementation of supplement protocols.

The legal status of nutritional supplements varies considerably across sporting organizations and jurisdictions, creating a complex regulatory landscape that athletes must navigate. The International Olympic Committee, the World Anti-Doping Agency, and national governing bodies maintain lists of

Table 1: Summary matrix of key ergogenic supplements in endurance contexts. Evidence ratings reflect the authors' grading of the narrative evidence reviewed in this manuscript (Strong = consistent findings across multiple randomized controlled trials and at least one position stand or meta-analysis; Moderate = some supporting randomized trials but heterogeneous findings or limited replication; Mixed = inconsistent or null findings across trials, or insufficient controlled evidence in endurance contexts). No pooled effect sizes or inferential statistics are implied.

Supplement	**Primary Mechanism**	**Typical Dose**	**Evidence Rating**	**WADA Status**
Caffeine	CNS stimulation; fatty acid mobilization; glycogen sparing	3–6 mg·kg^{-1}	Strong[a]	Permitted (Monitoring Program)
Ephedrine	Sympathetic stimulation; fat oxidation	–	Mod.[b]	Prohibited in competition
BCAAs	Central fatigue attenuation (limited)	10–20 g (trials)	Mixed[c]	Permitted
Phosphate	O_2 delivery (2,3-DPG)	–	Mod.[d]	Permitted
Glycerol	Hyperhydration; plasma volume	1 g·kg^{-1}	Mod.[e]	Permitted*
Creatine	ATP resynthesis; buffering	20–30 g·day^{-1} (loading)	Mod.[f]	Permitted
Sodium bicarbonate	Extracellular buffering; H^+ clearance	0.2–0.3 g·kg^{-1}	Strong[g]	Permitted
Beta-alanine	Intramuscular carnosine buffering	4–6 g·day^{-1}	Mod.[h]	Permitted
Nitrate (beetroot juice)	NO-mediated vasodilation; mitochondrial efficiency	6–13 mmol NO_3^-	Mixed[i]	Permitted

[a][1, 7]; [b][1, 13]; [c][1, 14]; [d][15]; [e][12, 16]; [f][8]; [g][2, 9]; [h][10, 17]; [i][11]. *Athletes should confirm current status with their national governing body; product contamination remains a general risk.

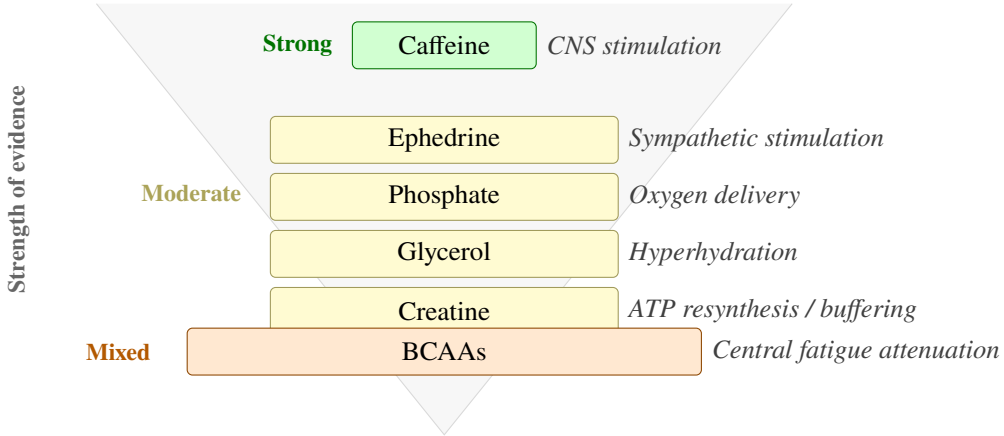


Figure 1: Evidence pyramid for ergogenic supplements in endurance sports. Supplements are arranged by the strength and consistency of available evidence (Strong, Moderate, Mixed), which reflects qualitative assessments of the literature rather than quantitative effect sizes.

prohibited substances that are updated regularly [1]. Caffeine was removed from the World Anti-Doping Agency (WADA) Prohibited List in 2004 and is currently included in WADA's Monitoring Program; it is not subject to a urinary concentration threshold that constitutes a doping violation. Ephedrine, by contrast, is prohibited in competition under the WADA Prohibited List. Creatine is universally permitted in competitive sport, although athletes should remain alert to the general risk of supplement contamination with prohibited substances; the regulatory status of other compounds, such as glycerol, should be confirmed with national governing bodies. The use of supplements that are not explicitly prohibited but lack regulatory oversight may pose additional risks, as product contamination with prohibited substances has been documented.

The ethical dimension of supplement use in sport extends beyond considerations of legality to encompass questions of fairness and the integrity of athletic achievement. Some authorities argue that any nutritional strategy that provides a competitive advantage beyond what can be achieved through training and diet alone is contrary to the spirit of sport. Others contend that supplements represent a legitimate extension of modern sports nutrition practice, similar to the use of specialized training facilities and technological devices. The distinction between acceptable nutritional interventions and prohibited substances is often blurred, creating difficult choices for athletes who seek to optimize performance while respecting the ethical standards of their sport.

The use of supplements by endurance athletes must be considered within the context of the overall training program, including considerations of psychological and physiological stress. As noted in Sections 6–9, the progressive overload of training, combined with the stress of competition, creates physiological demands that may exceed the capacity of whole foods alone to meet. Under these conditions, appropriately selected supplements may help athletes maintain training quality, reduce the risk of overtraining syndrome, and support the immune system during periods of intense preparation. The strategic application of supplements during periods of increased training load or when optimizing competitive performance may therefore be justified as a component of prudent sports science practice.

The role of the sports nutrition professional extends beyond the provision of supplement recommendations to include education regarding the principles of healthy eating and the limitations of supplement use. The establishment of a sound nutritional foundation through whole foods should remain the primary focus of dietary intervention, with supplements employed only when evidence supports their use and when practical constraints preclude adequate nutrient intake through food alone. The relationship between nutrition and training adaptation is complex, and simplistic approaches to supplementation may fail to address the underlying drivers of performance and recovery.

The ethical obligations of sports scientists and nutrition professionals to ensure athlete welfare require careful consideration of the potential benefits and harms of supplement use. The promotion of supplement use must be grounded in evidence-based practice, with due consideration of the athlete's health status, age, and developmental stage [2]. The provision of supplements that lack evidence for efficacy or safety is inconsistent with professional responsibility and may expose athletes to unnecessary risk. The monitoring of supplement use, including the assessment of individual responses and the documentation of any adverse effects, represents an important component of responsible practice.

The development of personalized supplement protocols that account for individual variations in physiology, metabolism, and practical constraints represents the next frontier in sports nutrition practice. Advances in genetic testing and metabolomics may provide insights into individual responses to specific nutrients and supplement strategies, enabling more targeted and effective interventions. However, the ethical implications of genetic testing must be considered, and athletes should not be disadvantaged by genetic variations that influence their response to supplements. The equitable application of sports

science knowledge requires consideration of access to advanced nutrition support and the potential for supplements to widen the gap between well-funded and less-resourced athletes.

The long-term health implications of supplement use represent an important area for future research, as current evidence primarily addresses short-term performance outcomes. While the supplements discussed in this review are generally recognized as safe when used within recommended ranges, the potential for interactions with medications, the development of adverse effects over extended periods of use, and the impact on future health outcomes merit ongoing investigation. The principle of "first, do no harm" should guide the approach of sports nutrition professionals to supplement recommendations, with the safety of the athlete remaining the paramount consideration.

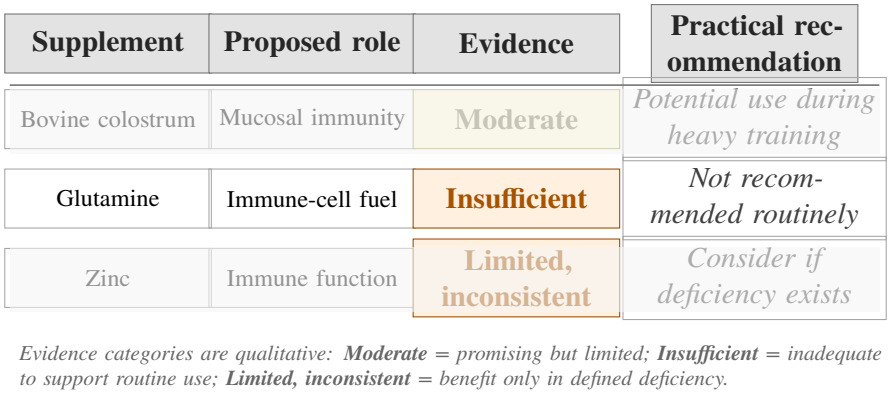


Figure 2: Categorical synthesis of immune-support supplements in endurance athletes. Bovine colostrum shows moderate promise, whereas evidence for glutamine is insufficient and evidence for zinc supplementation is limited and inconsistent. Routine prophylactic supplementation with glutamine or zinc is not supported in the absence of a specific deficiency.

10. Limitations and Future Research

This review has several limitations that warrant explicit acknowledgment. First, the evidence base for many of the supplements discussed is heterogeneous in dose, formulation, participant training status, and outcome measurement, which limits direct comparison across trials and precludes quantitative pooling within the scope of this narrative review. Second, several of the claims in Sections 6–8 rest on small trials or on position stands that synthesize evidence across mixed populations, and the extent to which findings generalize to elite or highly trained endurance athletes is uncertain. Third, the immune-function literature is particularly limited by small sample sizes, variable infection definitions, and a reliance on self-reported upper respiratory tract infection outcomes, which constrains the strength of conclusions regarding colostrum, glutamine, and zinc.

Future research should prioritize adequately powered randomized controlled trials in well-characterized endurance populations, with standardized dosing and outcome measures, to resolve the conflicting findings identified in Section 3. Specific priorities include: (i) direct comparisons of carbohydrate–protein formulations at different ratios and total carbohydrate intakes during recovery; (ii) trials of multiple-transportable carbohydrate formulations at intakes above 90 $g \cdot h^{-1}$ in trained athletes; (iii) mechanistic and outcome studies of BCAA supplementation that control for total protein and energy intake; (iv) long-term safety and immune-outcome trials of colostrum, glutamine, and zinc at supplemental doses; and (v) investigation of individual variability in supplement response, including the ethical implications of using genetic or metabolomic information to personalize supplementation. Research on the long-term

health effects of supplement use, and on the equitable accessibility of evidence-based nutrition support, is also needed to inform responsible practice.

11. Conclusion

The integration of targeted nutritional supplements into the training and competition routine of endurance athletes provides a means of addressing the key physiological challenges that limit performance, including dehydration, glycogen depletion, and exercise-induced immunosuppression. The evidence reviewed in this paper supports the strategic use of carbohydrates, proteins, and specific ergogenic compounds to support performance, recovery, and immune function during periods of intense training, although the strength of this support varies by compound and context, as summarized in Table 1. These conclusions should be read as conditional on adequate total energy and macronutrient intake, individual tolerance, and the regulatory status of each substance. The practical implementation of these strategies requires careful individualization, consideration of timing and dosage, and attention to the regulatory status of specific supplements.

The combination of carbohydrate and protein, often formulated at a 4:1 ratio, has emerged as an effective approach for supporting endurance performance when total carbohydrate intake is sufficient and recovery conditions are taken into account, with benefits reported across the pre-, during-, and post-exercise periods [3, 4]. The strategic manipulation of glycemic index and the timing of nutrient ingestion relative to exercise sessions can further enhance the benefits of supplementation, promoting sustained energy availability and accelerated recovery. Bovine colostrum shows moderate promise for supporting immune function during heavy training, whereas glutamine and zinc are not supported as routine prophylactics unless a specific deficiency is present [2, 9–11].

The development of comprehensive sports nutrition protocols that integrate supplementation with sound nutritional practices and appropriate training load management represents the current standard of practice in endurance athletics. Athletes who successfully implement these strategies may expect improvements in training quality, competitive performance, and overall health, although the magnitude of benefit is likely to vary with the athlete's baseline nutritional status, training load, and the specific supplement protocol employed, and should not be assumed to be uniform across individuals. However, the individualization of supplement protocols remains essential, as the metabolic requirements and tolerance of specific compounds vary among athletes. The ongoing refinement of sports nutrition practice through evidence-based research and practical experience will continue to enhance the performance of endurance athletes while maintaining the highest standards of ethical conduct and athlete welfare.

The practical guidelines derived from this review include recommendations for the timing and composition of pre-, during-, and post-exercise nutrition, as well as guidance on the selection of supplements for specific performance and immune support objectives. Athletes should work with qualified sports nutrition professionals to develop protocols that integrate these recommendations with their specific training demands and individual response characteristics. The implementation of these guidelines within the context of a comprehensive training program can help athletes achieve their performance goals while minimizing the risks associated with supplement use. The integration of legal and ethical considerations into the supplement decision-making process ensures that athletes can compete with integrity and confidence.

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