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Review Article

Bioactive And Sustainable Sports Nutrition*

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Abstract

The benefits of nutrition and physical activity for a healthy lifestyle are well-established. To enhance performance across various sports disciplines, athletes often incorporate a variety of supplements into their diets. Such supplements, commonly referred to as ergogenic aids, are widely used by athletes. The most commonly used ergogenic aids include creatine, caffeine, proteins, and amino acids, among which proteins are the most prevalent. Modern industrial food production significantly contributes to environmental degradation. It is projected that global dietary protein demand will continue to rise in the coming years, requiring substantially greater planetary resources. In response, alternative supplements derived from bioactive compounds are being developed as more environmentally friendly and functional options to support both athletic performance and health. Bioactive compounds characterized by a wide range of chemical structures and functions can be classified into subgroups such as carotenoids, phenolic compounds, glucosinolates, lignans, organosulfur compounds, and plant sterols. Due to their high antioxidant content and additional protein value, foods within these categories can contribute positively to athletic nutrition while also offering ecological benefits. The diverse applications of bioactive compounds support sustainable development. These compounds are believed to be effective in the treatment of chronic fatigue, cardiovascular diseases, and neurodegenerative disorders, while also enhancing athletic performance. Thus, bioactive and sustainable nutrition offers an alternative approach for athletes. In this context, further research into nutritional interventions is considered essential and valuable, especially within multidisciplinary frameworks.

Keywords: Athletic performance, Bioactive compounds, Nutrition, Sustainability.

INTRODUCTION

Nutrition is considered one of the fundamental pillars of athletic performance, and post-exercise nutritional recommendations are essential for effective recovery and adaptive processes. Therefore, an effective recovery strategy between training sessions or during competition can maximize adaptive responses against various mechanisms of fatigue, improve muscle function, and enhance exercise tolerance. The dietary pattern is effective in restoring an athlete's physical fitness by monitoring the quality and quantity of specified food components (Malsagova et al., 2021).

In addition to nutrient intake obtained from a regular diet, certain sports disciplines require the consumption of supplements that contribute positively to enhancing sports performance. These supplements, known as ergogenic aids, are defined as substances used to improve endurance, overall fitness levels, and sports performance. Some of these—such as creatine, caffeine, bicarbonate, proteins, and amino acids—have been used for different purposes: increasing energy intake, preserving strength, regaining muscle mass, or preventing nutrient deficiencies. Among the most marketed supplements in sports nutrition are proteins and amino acids. In fact, 80% of sports nutrition sales come from protein-based products, mostly in bar and powder formats, although the development of functional protein beverages has recently played a significant role. The current demand for more environmentally friendly products has increased research into more sustainable alternative protein sources (Arenas-Jal et al., 2020).

Sports nutrition has been the subject of numerous studies from past to present and is examined under a distinct medical discipline (Özer Altundağ & Payas, 2021a). The aim of this review is to summarize recent research related to new strategies in sports nutrition, focusing on alternative protein sources (insects, plant-based proteins, and mycoproteins), and to highlight the added value they provide in terms of bioactivity and sustainability. The benefits of protein hydrolysates and bioactive peptides on athlete performance, sports-related complications, and healthy aging, as well as the ergogenic effects of novel amino acids derived from natural sources, are also discussed. Additionally, future perspectives on protein supplementation in sports nutrition are addressed.

Sports Nutrition and Ergogenic Aids

Sports nutrition is essentially a specialized form of nutrition designed to maintain an athlete's performance and overall health. Each athlete's dietary plan is customized based on factors such as body mass index, age, gender, disability status, and various other considerations (Özer Altundağ & Payas, 2021b). Nutrition plays a crucial role in post-exercise recovery, providing the necessary elements for tissue repair, energy replenishment, and fluid balance. Protein intake is especially important, as it supplies the amino acids required to repair and rebuild muscle fibers that experience microtears during exercise—a process essential for muscle adaptation and growth (Bonilla et al., 2020). Adequate protein intake supports the restoration of muscle fibers and overall muscle stability, minimizing soreness and reducing the risk of injuries such as strains and sprains, particularly in high-impact sports (Howatson et al., 2012). Additionally, glycogen depleted during intense activity must be replenished through carbohydrate intake to prepare muscles for future performance demands (Alghannam et al., 2018). Targeted nutritional protocols can further enhance recovery; studies suggest that branched-chain amino acids (BCAAs) may help reduce muscle soreness and fatigue, thereby lowering the risk of injury (Khemtong et al., 2021).

The role and necessity of dietary supplements in recovery can vary according to athletic level. For elite athletes engaged in rigorous training regimens, supplementation is often essential to meet high nutritional demands and support rapid recovery and optimal performance. Their demanding schedules may prevent them from fulfilling these needs through diet alone, making supplementation a valuable tool in maintaining a competitive edge. In contrast, amateur athletes with less intense training loads can often meet their nutritional requirements through a balanced diet without relying on supplements. Recognizing these differences helps tailor nutritional recommendations to align with the specific demands of athletes at different levels (Wang et al., 2024).

Nutritional ergogenic aids are substances included in the category of sports supplements. Dietary supplements are widely used among athletes; however, evidence-based analysis is needed to support their effectiveness in enhancing training outcomes or competitive performance in specific disciplines (Vicente-Salar et al., 2022; Abreu et al., 2023). Commonly used ergogenic aids among athletes include creatine, caffeine, proteins, and amino acids (Peeling et al., 2018; Pickering et al., 2019; Hall et al., 2021).

Creatine

Creatine is one of the most popular nutritional ergogenic aids for athletes. Studies have shown that creatine supplementation increases intramuscular creatine concentrations, leading to enhanced adaptations to training by improving high-intensity exercise performance. In addition to its benefits in athletic and exercise performance, research indicates that creatine supplementation may enhance post-exercise recovery, injury prevention, thermoregulation, rehabilitation, and provide neuroprotection against concussions and/or spinal cord injuries. Furthermore, the clinical applications of creatine have been investigated in relation to a range of conditions, including neurodegenerative diseases (e.g., muscular dystrophy, Parkinson’s disease, Huntington’s disease), diabetes, osteoarthritis, fibromyalgia, aging, brain and cardiac ischemia, adolescent depression, and pregnancy. It is believed that creatine not only improves exercise performance but may also play a role in preventing and/or reducing injury severity, enhancing rehabilitation outcomes, and aiding athletes in tolerating heavy training loads. Additionally, researchers have identified several potential clinical uses for creatine supplementation. Both short- and long-term supplementation (up to 30 g per day for five years) has been shown to be safe and well-tolerated. Moreover, habitual lifelong intake of low-dose dietary creatine (e.g., 3 g per day) has been reported to confer significant health benefits (Kreider et al., 2017).

Caffeine

Caffeine supplementation has been shown to acutely enhance exercise performance. Its use affects muscular endurance, movement velocity, muscle strength, sprinting, jumping, and throwing performance, as well as a wide range of aerobic and anaerobic sport-specific activities. Among these, aerobic endurance appears to benefit the most consistently, with moderate to large performance improvements observed, although the magnitude of these effects varies among individuals. Caffeine has consistently been demonstrated to improve exercise performance when consumed in doses of 3–6 mg per kilogram of body weight. The minimum effective dose of caffeine remains unclear but may be as low as 2 mg/kg, while very high doses (e.g., 9 mg/kg) have been associated with a higher incidence of side effects. The most common timing for caffeine supplementation is approximately 60 minutes prior to exercise. However, the optimal timing may depend on the specific source of caffeine. Individual variability in response to caffeine in sports and exercise settings as well as potential adverse effects such as sleep disturbances or increased anxiety may be attributed to genetic differences in caffeine metabolism, as well as physical and psychological responses. Other factors, such as habitual caffeine consumption, may also contribute to inter-individual differences in response. Caffeine has been shown to have ergogenic effects on cognitive function, particularly in enhancing alertness and attention in most individuals. Moreover, energy drinks and pre-workout supplements containing caffeine have been reported to improve both anaerobic and aerobic performance (Guest et al., 2021).

Protein and Amino Acids

Dietary protein is essential for supporting growth, repairing damaged cells and tissues, synthesizing hormones, and facilitating various metabolic activities. Numerous protein sources are available; however, while animal-based proteins contain all essential amino acids and are considered complete protein sources, plant-based proteins are often lacking in one or more essential amino acids and are thus classified as incomplete. Individuals engaging in intense training require higher dietary protein intake than sedentary individuals (i.e., 1.4–2.0 g/kg/day). Intake of protein and/or amino acids before, during, and/or after exercise appears to enhance recovery, support immune function, and promote the growth and maintenance of lean body mass. Consequently, protein and amino acid supplementation may serve as a convenient means for athletes to ensure timely and/or adequate intake. Adequate intake and proper timing of protein consumption have been shown to be beneficial across various exercise modalities, including endurance, anaerobic, and resistance training (Kreider & Campbell, 2009).

In situations where adequate protein intake cannot be achieved through diet alone, supplementation has been reported to improve performance (Abreu et al., 2023). Essential amino acids (EAAs), which cannot be synthesized by the human body, are critical components of protein intake. Initial studies on the effects of EAAs on skeletal muscle highlight their primary role in stimulating muscle protein synthesis (MPS) and turnover. Protein turnover is crucial for replacing damaged muscle proteins and establishing the metabolic basis for improved functional performance. In individuals without inborn metabolic disorders, the safe upper limit of EAA intake can readily accommodate supplementation. At rest, MPS stimulation can occur at relatively low doses (1.5–3.0 g) and plateaus around 15–18 g. Repeated EAA-induced MPS stimulation throughout the day does not diminish the anabolic effect of meal intake. Although direct comparisons between various formulas have not yet been fully explored, overcoming age-related anabolic resistance marked by reduced muscle sensitivity may require higher leucine content. Even in the absence of exercise, EAA supplementation has been shown to improve functional outcomes in anabolic-resistant populations. EAA requirements increase during caloric deficits. Therefore, meeting whole-body EAA needs is essential to preserve anabolic sensitivity in skeletal muscle during energy restriction (Ferrando et al., 2023).

BCAAs are among the most popular sports supplements, often marketed based on the assumption that they enhance muscle adaptation. Despite widespread consumption among athletes and the general public, the effectiveness of BCAAs remains a topic of ongoing debate within the field of sports nutrition. Early support for BCAA supplementation stemmed from extrapolated mechanistic data regarding their roles in muscle protein metabolism. Among the three BCAAs, leucine has received the most attention due to its ability to stimulate the initial acute anabolic response (Plotkin et al., 2021).

Over the past decade, insects have been recognized as one of the most environmentally friendly sources of animal protein, as their carbon and water footprint are very low. In general, these insects contain large amounts of chitin, an insoluble polysaccharide composed of N-acetylglucosamine units derived from their exoskeleton. Furthermore, they offer high levels of vitamins and minerals compared to other conventional food sources, along with excellent production efficiency (Kim et al., 2019). Insects possess a high protein content (40-60%), comparable to conventional animal protein sources such as eggs, milk, or meat (Churchward-Venne et al., 2017). Additionally, they exhibit a favorable amino acid profile, with averages for most EAAs and BCAAs exceeding the levels recommended by the World Health Organization (WHO) (WHO, 2007).

Sustainable Nutrition

Sustainability is a challenging concept to define due to its applicability across a wide range of discussion contexts. The United Nations Brundtland Commission’s 1987 conceptualization defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Smetana et al., 2019). Environmental, economic, health, nutritional, and other related dimensions are intrinsically interconnected. In this context, sustainable diets and nutritional models those that exert minimal environmental impact, significantly contribute to food and nutrition security, support healthy living outcomes for current and future generations, and are economically accessible while optimizing both natural and human resources are of critical importance (Burlingame, 2014).

Integrating the dimensions of nutrition and sustainability is a complex task addressed by several scientific paradigms. These paradigms encompass the multiple dimensions and functions of food systems that aim to offer solutions for the harmonious co-evolution of humanity and the planet Earth (Smetana et al., 2019).

Diets must be healthy, nutritionally adequate, and safe. Accordingly, the intake of foods associated with various non-communicable diseases such as refined sugars, saturated fats, and sodium should be reduced, while the inclusion of beneficial nutrients such as proteins, fiber, minerals, and vitamins should be encouraged. Furthermore, nutrition should be proactive, offering health-promoting benefits tailored to specific needs such as digestive health, immune support, and healthy, active aging. Food waste and loss must be minimized at every stage of the food chain, and the focus should shift toward sustainable protein sources, including plant-based proteins, insect proteins, cellular agriculture, and precision fermentation. Identifying culturally appropriate sources of various nutrients is key to sustaining the long-term health and survival of diverse populations worldwide (Asghar & Khalid, 2023).

Bioactive Sustainable Food Sources

The bioactive components in the structure of functional foods play a significant role in maintaining health and preventing many diseases such as asthma, viral and parasitic infections, and inflammatory disorders (Castillo et al., 2018). Therefore, the consumption of foods containing these components has gained great importance (Uyar & Sürücüoğlu, 2010). Carotenoids, n-3 fatty acids, isoflavones, flavonoids, isothiocyanates, phenolic acids, phytoestrogens, polyphenols, soluble dietary fibers, plant stanols and sterols, polyols, probiotics, prebiotics, and synbiotics are defined as "bioactive components" (Ashwell, 2002). Plant-based foods have become a sustainable alternative in food systems due to their significantly lower greenhouse gas emissions and their richness in bioactive compounds and/or plant-based proteins (Khan et al., 2023). Bioactive compounds found in edible plants and foods are vital for both human and planetary health. These natural bioactives, as components of whole diets, ingredients, or supplements, can regulate numerous aspects of human health and well-being. Innovation in this field is essential for sustainably and healthily feeding the growing global population. This requires substantial changes in our food system, encompassing agriculture, production, distribution, and consumption (Kussmann et al., 2023).

Polyphenols ingested through diet are metabolized in the human body via various biotransformations, leading to compounds with different bioactivities (Contente et al., 2021). Carotenoids, ubiquitous isoprenoids found in foods that have always been part of the human diet, can be converted into retinoids exhibiting vitamin A activity essential for humans. Moreover, they are multifunctional, serving not only as vitamin A sources but also as natural pigments, antioxidants, and health-promoting compounds in foods (Meléndez-Martínez et al., 2022).

Polyphenols are plant compounds with diverse biological activities (Pérez-Jiménez et al., 2023). Fruits, vegetables, and other edible plants in the diet confer numerous health benefits primarily due to these bioactive compounds, including polyphenols (Ahmad et al., 2022). A polyphenol-rich diet provides protection against chronic pathologies by regulating numerous physiological processes such as cellular redox potential, enzymatic activity, cell proliferation, and signaling pathways. Major dietary polyphenols including resveratrol, curcumin, quercetin, rutin, genistein, daidzein, ellagitannins, and proanthocyanidins are extensively studied pharmacokinetically (Luca et al., 2020). Fruits, cocoa products, tea, and wine are primary sources of phenolic compounds in human nutrition. These compounds are present throughout the plant, including roots, leaves, and fruits. Consequently, leaves and stems primarily contain higher amounts of these compounds, mostly in monomeric forms, while polymeric polyphenols are found in vacuoles, leaves, epidermis, flowers, and fruits (Del Rio et al., 2013; Pérez-Jiménez et al., 2010). Currently, certain plants are used to increase muscle strength and body mass. The health benefits of plants are attributed to bioactive compounds such as polyphenols, terpenoids, and alkaloids, which exert various physiological effects on the human body (Sellami et al., 2018).

Nature produces foods composed of countless combinations of macronutrients, micronutrients, phytonutrients, prebiotics, probiotics, and other bioactive compounds. These nutrients exist not in isolation, but within a matrix of constituents acting upon a range of enzymatic and metabolic targets. Humans are complex organisms, yet the prevailing reductionist and mechanistic approach to nutrient evaluation attempts to isolate these systems into discrete units and address them independently; it isolates the part from the whole. Consequently, taking a complex plant extract or food possessing multiple active compounds and isolating them towards a single mechanistic target fails to capture their multi-targeting effects. For instance, the combination of vitamins C and E has been demonstrated to protect cells from oxidative damage to a greater extent than each nutrient alone. Furthermore, zinc status has been shown to influence the transport, metabolism, and utilization of vitamin A within the body. Additionally, magnesium consumed in the form of leafy greens exhibits higher bioavailability than that obtained from cereal products. Regarding supplementation, magnesium in specific forms (e.g., magnesium glycinate, citrate, chelated) possesses greater bioavailability in the human body compared to other forms such as magnesium oxide (Pardo et al., 2021; Townsend et al., 2023).

Bioactive and Sustainable Nutrition in Athletes

The increasing human population and scarcity of highly valuable protein components have driven the international community to seek new, sustainable, and natural protein sources from invertebrates (e.g., insects), underutilized legumes, terrestrial and aquatic wild greens, and fungi. Insect proteins are nutritionally valued for their richness in proteins with a good balance of essential amino acids and as important sources of essential fatty acids and trace elements (Quintieri et al., 2023).

Demand for clean-label, allergen-free, and plant-based products is rising. Concerns related to sustainability, animal welfare, and ethics are increasing the demand for new alternatives to animal proteins (Radnitz et al., 2015). A well-designed vegan diet can provide sufficient energy and adequate intake of carbohydrates, fats, and proteins to support performance (Lynch et al., 2016). Some plant-based proteins have been shown to be as effective as animal proteins for muscle maintenance and can supply all essential amino acids (Mangano et al., 2017). Vegetarian endurance athletes exhibit greater cardiovascular fitness compared to their omnivorous peers, although peak torque does not differ between diet groups. These data suggest that vegetarian diets do not negatively affect performance outcomes and may facilitate aerobic capacity in athletes (Lynch et al., 2016).

Adequate dietary protein is essential as exercising individuals require increased amounts. When assessing protein quality, animal protein sources routinely rank highest. However, considering the positive health effects of increased plant intake and environmental sustainability, interest in consuming more plant proteins is steadily growing. Numerous studies indicate that a plant protein dose providing sufficient essential amino acids, especially leucine, consumed over 8–12 weeks can stimulate adaptations similar to those observed with animal protein sources, facilitating long-term exercise training adaptations (Kerksick et al., 2021). Most plant-based proteins have low essential amino acid content and are often deficient in one or more specific amino acids such as lysine and methionine. However, large differences exist in amino acid composition among various plant protein sources. It is reported that plant proteins can offer a more balanced amino acid profile through diverse sources, potentially approximating the amino acid profile of animal proteins (Pinckaers et al., 2021).

Alternative protein sources, such as insects, plants, or mycoproteins, have proven to be an interesting substrate due to their high added value in terms of bioactivity and sustainability. Protein hydrolysis has been demonstrated to be a highly useful technology for valorizing by-products, such as collagen, by producing beneficial bioactive peptides that impact athletic performance and exercise-related complications. Additionally, specific amino acids derived from plant sources, such as citrulline or theanine, have been observed to possess ergogenic effects for this target population (López-Martínez et al., 2022).

Probiotic administration significantly prolonged the time to reach maximum concentrations of methionine, histidine, valine, leucine, isoleucine, tyrosine, total BCAAs, and total EAAs (Jäger et al., 2020). The green tea amino acid L-theanine (L-THE) is associated with various health benefits, including mood improvement, cognition, and reduction of stress and anxiety-like symptoms. Supplementation with 200–400 mg/day L-THE may help reduce stress and anxiety in individuals exposed to stressful conditions (Williams et al., 2020).

Dietary fiber, a nutrient found in plant foods, provides different health benefits based on its physicochemical properties (solubility, viscosity) and physiological effects (fermentability). Additionally, plant foods contain more than dietary fiber and are rich sources of bioactives that also provide health benefits (Timm et al., 2023).

Microgreens are rich in vitamins and minerals to ensure micronutrient adequacy. Fresh and processed microgreen-based products with high nutrient density can enhance food diversity and nutritional value (Seth et al., 2025). Sweet potato leaves have been reported to contain various antioxidants linked to high polyphenol, flavonoid, and carotenoid levels, contributing to physiological defense against oxidative and free radical-mediated reactions, suppressing low-density lipoprotein (LDL) oxidation and deoxyribonucleic acid (DNA) damage in human lymphocytes (Nguyen et al., 2021). Being potential sources of micronutrients and functional compounds, microgreens are considered sustainable products that can be further developed for food and medical industries. Legumes such as lentils, beans, chickpeas, and peas are gaining popularity due to their environmental sustainability, nutrient density, and functional properties. The protein content and quality of legumes vary among classes and processing methods. The biological properties of their proteins and physiologically active peptides make legumes attractive as potentially functional or health-promoting foods. The protein quality of legume proteins determined by Protein Efficiency Ratio and Protein Digestibility Corrected Amino Acid Score, as well as bioactive peptides linked to improvements in hypertension and diabetes, highlight their bioactive properties. Overall, legume-based proteins exhibit high nutritional quality, supporting the benefits of legume inclusion in the diet and demonstrating beneficial bioactivities that may improve outcomes in non-communicable diseases (Nosworthy et al., 2025).

Seaweed contains essential amino acids, vitamins, minerals, and antioxidants. Its protein content ranges from 11% to 32% of dry weight, making it valuable for various diets, including vegetarian and vegan. Seaweed protein production highlights sustainability and environmental advantages compared to traditional sources. Seaweed cultivation requires minimal resources and mitigates environmental issues such as ocean acidification (Pereira et al., 2024). Fava beans possess high protein content and a well-balanced amino acid profile, along with bioactive components such as bioactive peptides, phenolic compounds, GABA, and L-DOPA, which have health-promoting properties (Martineau-Côté et al., 2022). Legumes and nuts hold high importance in many countries' diets, especially in the Mediterranean region. They are versatile and culturally diverse foods found worldwide and serve as a primary protein source in some countries (Hernández-López et al., 2022).

Furthermore, anti-inflammatory foods with high bioavailability, such as cherry juice and turmeric, have been shown to reduce exercise-induced inflammation and alleviate muscle soreness (Kimble et al., 2023; Gray et al., 2014). Anthocyanins (ACNs), a subclass of (poly)phenols responsible for the red-blue-purple pigmentation of fruits and vegetables, have attracted significant interest in sports and exercise research due to their potential to facilitate post-exercise recovery (Kimble et al., 2023).

Although supplements such as creatine, caffeine, carbohydrate-electrolyte drinks, cherry juice, beetroot juice, and mineral sodium bicarbonate are known to affect athlete performance, cherry juice has been reported to be more effective in repairing muscle damage after exercise or matches, while beetroot juice is more effective in enhancing recovery (Abreu et al., 2023).

CONCLUSION

Integrating sustainable, highly bioactive foods with personalized nutrition provides a comprehensive framework for enhanced recovery, greater resilience to physical stress, and improved performance in athletes. Strategies to overcome barriers in the consumption of insect products include emphasizing their sustainability, enhancing their palatability, and improving the ability to incorporate insects into familiar food products. An emerging industry focused on insects for food and feed is taking shape. Key challenges encompass regulatory frameworks, reducing costs through automation and the use of low-cost substrates, developing insect-based products appealing to consumers, and investigating their health benefits. It should also be taken into consideration that the toxic effects of alternative sources in bioactive and sustainable sports nutrition are taken into account and that separate clinical studies should be conducted to determine the possible side effects on athletes.

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