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The Role of Enzymatic Activity in Enhancing Athletic Performance: A Biochemical Evaluation of Nutritional Supplement Efficacy in Sport Science

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Abstract:

Athletic performance is intricately linked to biochemical processes that govern energy metabolism, muscle contraction, and recovery, with enzymatic activity serving as a central determinant of physiological efficiency. Nutritional supplements that target key enzymes such as creatine kinase, ATPase, lactate dehydrogenase, and mitochondrial oxidases have gained prominence in sport science for their potential to enhance performance outcomes across strength, power, and endurance domains. This position paper critically evaluates the biochemical mechanisms by which these supplements influence enzymatic pathways, synthesizes empirical evidence supporting their efficacy, and examines the ethical, safety, and regulatory considerations associated with their use. Key issues discussed include fair play, athlete autonomy, contamination risks, long-term health effects, and compliance with World Anti-Doping Agency (WADA) regulations. The paper argues that, when implemented responsibly under professional supervision and evidence-based protocols, enzyme-targeted nutritional supplementation constitutes a legitimate biochemical strategy for performance optimization. However, responsible use requires careful adherence to ethical principles, safety guidelines, and equitable access to resources. This synthesis provides a comprehensive framework for athletes, sport scientists, and policymakers seeking to integrate biochemical supplementation into contemporary sport practice while safeguarding integrity and athlete welfare.

Keywords: Enzymatic activity; Athletic performance; Nutritional supplements; Sport science; Metabolic pathways; Ethical considerations; Anti-doping compliance.

Introduction

The ultimate result of biochemical and physiological processes that govern energy metabolism, muscle contraction, recovery, and training stimuli adaptation is the athletic performance in sprinting, weightlifting, endurance running, or team sports (Joyce & Lewindon, 2023). Of key importance among such processes is enzymatic activity: enzymes serve as biological catalysts that enhance metabolic reactions so that they can produce and decompose adenosine triphosphate (ATP), the main energy currency of the cell, very quickly. In the absence of efficient enzyme functioning, energy systems would fail to sustain the need for vigorous or prolonged exercise to deliver energy, restricting energy output, endurance ability, as well as total performance potential (Smith et al., 2024). As such, it is essential to learn the nature of the enzyme and to ensure that it functions optimally to achieve the best out of sportspeople.

Other than the production of energy, recovery processes, metabolic homeostasis, and repeated training adaptation are based on enzymatic systems. As an example, antioxidant defense enzymes reduce reactive oxygen species (ROS) produced during high-intensity exercise and eliminate oxidative damage of muscle fibers, accompanied by recovery (Tkaczenko & Kurhaluk, 2025). In addition, the trainings promote metabolic adaptation in enzyme profiles in glycolysis, oxidative phosphorylation and biogenesis of the mitochondrial body, which change substrate use, energy expenditure and resistance to fatigue in the long-term (Lee and Kim, 2024). The growth of athletic capacity is built around these adaptations, which implies that the role of enzymatic regulation is not only vital during an exercise bout (acutely) but also during training (chronically) which determines the process of adaptation of the athletes to training stimuli.

With the focus on the central role of enzymatic events, the recent interest in nutrition and, specifically, in supplementation as a way of assisting or stimulating enzyme-mediated metabolism has increased. Dietary supplements are popular in sport science because they can provide substrates, cofactors, or precursors that can support optimal enzyme activity thus contributing to better metabolic performance, fatigue procrastination, or recovery (Rodriguez et al., 2025). Some of the most researched include supplements like creatine monohydrate and amino acid 2 alanine which have been shown to affect the availability of intramuscular substrate and buffer capacity of muscle respectively (Durkalec-Michalski et al., 2021). The rationale behind this is biochemical: by increasing the supply of metabolites or improving the intracellular environment, these supplements can enhance the performance and stability of enzymatic activities during high-intensity or repeated exercise.

This biochemical argument is supported by its empirical evidence. An example is the Creatine combined with 2-alanine supplementation which of late has been linked to better work at high-intensity exercise, specifically, anaerobic power and repeated-bout performance compared to either of the two supplements (Systematic review, 2025). This indicates that supplementation has the potential to improve the ability of the body to generate and use energy in harsh environments probably via improved phosphagen and buffering mechanisms that depend on enzyme-mediated processes. As the influences on maximal strength and alteration of body composition are more inconsistent (and even minor), there is more evidence of better explosive power and repeated high-intensity efforts performance (Knoblauch, 2024).

However, the application of supplements to control biochemical pathways would create some crucial issues of efficacy, context-dependency and long-term adaptation. Not every study is equally beneficial, and some studies in endurance-based sports (e.g., swimming) have found no or small effect of creatine supplementation on performance, physiological response, and body composition (Sports Medicine – Open, 2024). It can be implied that the ergogenic utility of supplementation can be largely dependent on the sport discipline, the type of performance requirement (anaerobic and aerobic) and the training condition of the athlete. Hence, the issue of supplement efficacy needs to take into account the context of application i.e. the nature of sport activity, training history of an athlete and metabolic requirements of sport.

Considering all these accumulating facts, the biochemical centrality of enzymes to metabolism and recovery, the potential of nutritional supplements to regulate substrate availability and metabolic milieu, and the empirical evidence of performance improvements under specific circumstances, it is evident that the optimization of enzymatic activity through the well-designed use of nutritional supplements should be viewed as one of the core methodologies in the modern sport science. The paper will assume that a more biochemical assessment of supplement efficacy, especially the use of enzyme-mediated metabolism, presents a scientifically based and ethically sustainable avenue of improving the performance of athletes, in combination with a proper training regimen and individualized athlete requirements.

Conceptual Clarification

Enzymatic Activity

Enzymatic activity is the speed and efficiency of the enzymes in the body which are specialized proteins in catalyzing biochemical reactions. Enzymes are utilized to create and enhance roughly 400 daily consumer and industrial items. They are utilized in food and drink processing, animal nutrition, textiles, home cleaning and fuel for automobiles and energy production (Nwikiri et al., 2025). Over muscle physiology as well as athletic performance, enzymes regulate important metabolic activities including the production of ATP (adenosine triphosphate), energy movement, and breakdown of substrates.

As an example, phosphocreatine (PCr) can be converted to creatine and ATP with the help of Creatine kinase (CK); a reaction that is essential to fast and high-intensity efforts that last only a few seconds such as sprinting or weightlifting (Nasikhah et al., 2021). In the same way, enzymes such as Lactate dehydrogenase (LDH) control anaerobic glycolysis by catalyzing the

reversible conversion of pyruvate into lactate which affects the way muscles process metabolic byproducts during anaerobic stress (Bartoloni et al., 2024). In the absence of effective enzymatic activity, the production of ATP and provision of energy would be slower than the demand, which would cause fatigue and deteriorated performance.

Further, enzymatic activity is dynamic and adaptive: training (endurance and resistance) induces an enzyme expression, density and isoform distribution changes in muscle fibres demonstrating metabolic fibre-type changes and an increase in capacity. As an example, physically trained people have a higher level of active mitochondrial enzymes (e.g. citrate synthase) and changed isoenzyme (e.g. more oxidative isoforms of LDH) profiles that represent a change to high aerobic capacity and metabolic efficiency (Glancy et al., 2021). These adaptations enhance the muscle to maintain the long-term functioning level, endurance, and faster recovery. Thus, enzymatic activity is not an unchanging characteristic, it is developed under training, nutrition, and rest, and it is the key to both the acute performance and adaptation to the long-term.

Athletic Performance

Athletic performance is a complex construct that incorporates the physiological, biochemical, neuromuscular, and technical tactical dimensions, which brings a quantifiable result: speed, strength, endurance, and power. Biochemical and physiological factors determine the ability of an organism to produce and use energy, handle metabolic waste, and rest between exercise episodes and the ability to recover is crucial to performance. High efficiency of energy metabolism facilitated by enzyme activities promotes quick recovery of ATP, postpones fatigue onset and allows repeated high-intensity exercise or prolonged endurance exercise. Therefore, enzymatic activity is a direct factor to the most important performance indicators, including top speed in sprints, height of jump, power production, and overall endurance (Glancy et al., 2021).

However performance is not entirely dependent on biochemistry. It is a complex product of training history, neuromuscular coordination, fibre type composition, psychological preparedness and external conditions (e.g. nutrition, environment). However, biochemically speaking, enzymatic efficiency is a bottom layer: at optimal working conditions of enzymes, the body is able to convert training and physiological potential into performance to the highest degree possible. This biological premise is particularly pertinent in the case of sportspeople whose career requires vigorous, recurrent, or prolonged actions in which each fraction of a

second, watt of strength or repetition matters. This means that any activity that boosts or affects the enzyme activity would have profound effects on the end sporting performance.

Biochemical Evaluation

Biochemical evaluation means the regular quantitative and analytical assessment of biochemical markers, metabolic inflows, enzyme functions, substrate concentrations, and other molecular or cellular indicators that represent the physiological condition of an organism internally. Biochemical analysis in sport science research. In sport science research, biochemical analysis is frequently performed on blood, muscle, biopsy or metabolic samples to evaluate variables which include enzyme activities (e.g., CK, LDH, citrate synthase) and concentrations of metabolites (e.g. lactate, phosphocreatine, ATP) and oxidative stress markers and mitochondrial workability. These assessments enable scholars to correlate molecular-level modifications with functional performance (e.g. performance, fatigue, recovery) thus illuminating the processes that spearhead athletic performance and adaptation (Tupling et al., 2025).

Several benefits of this molecular level analysis are: (1) it can isolate the physiological mechanisms behind performance gains or fatigue (e.g. energy metabolism, oxidative stress, recovery), (2) it can be used to provide more specific interventions (nutritional, training, recovery), and (3), it can be used to track the response to training or supplementation over a period of time. Indicatively, the mitochondrial enzyme augmentations (like citrate synthase) following some duration of aerobic training are related to enhanced oxidative ability and endurance performance (Place and Baar, 2003). Likewise, it can be determined through enzyme isoform shift or substrate availability assessment to identify transitions in fibre type, metabolic flexibility, or metabolic strain, which can help explain variations in responses of athletes. Simply put, sport science has been rooted in biochemical testing and validated by empirical, quantifiable physiology that can be subjected to evidence-based solutions and not unproven assertions.

Nutritional Supplement Efficacy

The efficacy of nutritional supplements can be defined as the extent to which dietary supplements (ergogenic aids, amino acids, metabolic precursors, etc.) can give the desired physiological or performance effect as shown under controlled or natural conditions. Randomized controlled trials (RCTs), meta-analyses or systematic reviews of efficacy are

commonly conducted with respect to performance outcomes (strength, power, endurance), biochemical (enzyme activity, metabolite levels) or recovery (index) or training adaptations (in sport science). As an example, current meta-analytic studies have demonstrated that Creatine and 2 Alanine supplements have the potential to enhance explosive power and sprint performance when used in conjunction with training and this highlights their practical ergogenic applicability (Deng et al., 2025). Therefore, the efficacy of supplements extends beyond the biological plausibility it must have quantifiable sports or body effects.

Nevertheless, efficacy is usually situational and relative. Based on a critical review, although supplements such as creatine, 2-alanine, branched chain amino acids (BCAAs), caffeine, and nitrates have been the most studied ergogenic aids, their effects on performance are sport-dependent, training level of the athlete, dose schedule, and duration of supplementation (Kaufman, Roche & Fredericson, 2022). To illustrate, creatine may be of substantial benefit in sprinting, weightlifting or team sports (where explosive power is required) and not of much benefit in simply endurance sport. Also, despite the fact that certain supplementation regimens can enhance jump height or sprint speed, in most studies these factors have little or no influence on muscle hypertrophy or maximal endurance (Ashtary Larky et al., 2025). Therefore, efficacy has to be assessed in terms of particular performance requirements, and the researchers or practitioners should be careful not to extrapolate the benefits to all sporting situations.

Sport Science

Sport science is a multidisciplinary field which unites the fields of physiology, biochemistry, nutrition, biomechanics, psychology, as well as training pedagogy which seeks to maximize athletic performance, health, and adaptation. On the biochemical side of sport science, there is research into the effects of metabolic pathways, enzymatic processes, nutritional contributions, and recovery strategies on the performance outputs, training adaptation, injury and long-term development of athletes. Within this context, biochemical variables (activity of the enzymes, metabolic levels, efficiency of the mitochondria, and availability of substrates) are considered as adjustable determinants of performance that can be modified according to training, diet, supplementation, and recovery measures (Place and Baar, 2003; Mazzeo and Green, 2014).

Notably, sport science concentrates on individualized and evidence-based methods. Due to the genetic diversity of athletes, training experience, nutritional condition, fibre-type kinetics, sport activity, interventions (such as supplements) are not universal. Using stringent biochemical analysis, sport scientists are able to determine whether a nutritional or training intervention has

a significant impact on particular metabolic pathways of interest to a particular athlete. This facilitates customized performance enhancement, reduces extraneous or counterproductive supplementation and facilitates safe and ethical practices especially among elites or competitive settings. Sport science thus offers the gap between basic biochemistry and realistic athletics.

Enzymatic Activity as the Foundation of Athletic Performance

The biochemical foundation of human performance is enzymatic activity since the rate and efficiency of the reaction that determines energy generation, muscle contraction, and recovery are controlled by enzymes. Exercise causes the body to use three broad systems of energy, phosphagen, anaerobic glycolysis, and oxidative phosphorylation and each system utilizes different types of enzymes to produce ATP at a pace that is sufficient to serve the body. Evidence from exercise biochemistry shows that the absence of the catalytic functions of essential enzymes would slow ATP turnover so that even moderate-intensity exercise cannot be maintained (López-Fernández et al., 2021). Therefore, enzymes are not just facilitating biochemical elements but the core of metabolic power, which defines the efficiency with which athletes can transform substrates into usable energy.

Creatine kinase (CK), which facilitates rapid resynthesis of ATP (derived from phosphocreatine) during explosive efforts, is a large enzyme in high-intensity performance. Immediate availability of energy to sprints, jumping and rapid force production is made possible by CK activity. The latest results indicate that high-power endurance athletes have much higher CK turnover rates and more efficient phosphocreatine shuttling than non-athletes, which can more quickly resynthesize ATP and compensate for metabolic lag during maximal exertion (Zhang et al., 2022). Phosphocreatine transport system provided by cytosolic and mitochondrial isoforms of CK has been found to provide enhanced muscle contractile activity and biochemical rationale in the application of creatine supplementation in sports.

When the exercise is continued beyond several seconds, the body moves to anaerobic glycolysis, with lactate dehydrogenase (LDH) having a central role. LDH controls the process of pyruvate to lactate conversion, which enables the glycolysis process to proceed to produce ATP even in situations of low oxygen supply. Modern literature attests to the fact that athletes with an elevated LDH activity have a high tolerance to high-intensity intermittent exercise because of the better processing of lactate and faster glycolytic turnover (Ishikura et al., 2023). Instead of acting as an indicator of fatigue, lactate is currently being viewed as a vital

intermediate, which helps maintain metabolic flexibility, and the activity of LDH is a direct predictor of the ability of muscle cells to utilize this metabolite during intense workload.

ATPase is another enzyme that cannot be dispensed as it breaks down ATP to give energy to contract the muscles. The contraction speed is set by myosin ATPase, and relaxation and excitation contraction coupling are controlled by sarcoplasmic reticulum Ca 2 ATPase. Originally, anaerobic glycolysis results in high ATPase activity which promotes rapid cross-bridge cycling and effective muscle mechanics. A recent study of muscle physiology indicates that trained athletes, especially sprint and strength athletes, are able to display an upregulation of ATPase activity in fast-twitch muscles, which allows them to generate forces more quickly and contract more rapidly (Sweeney and Tikunov, 2021). This adaptive mechanism of enzymes is an important point of difference between elite athletes and amateur athletes.

In addition to the high rate of ATP turnover, protracted or repeated exercise labor is supported by enzymes in the mitochondrion, particularly those that are connected to oxidative phosphorylation, including cytochrome c oxidase, citrate synthase, and succinate dehydrogenase. These enzymes control aerobic ATP production and they are highly stimulated by endurance training. Mitochondrial physiological evidence indicates that endurance athletes have significantly increased the density of mitochondria and the activity of oxidative enzymes, which enables them to produce ATP, accumulate less lactic acid, and recover more quickly after a workout (Granata et al., 2020). This underscores the role played by oxidative enzymatic capacity in high-level performance of endurance.

Combined, these metabolic processes show that athletic performance is essentially the ability of the enzymes in their expression. The athletes having increased activity of CK, LDH, ATPase and oxidative enzymes have the ability to produce better power, fatigue resistance, metabolic efficiency and training adaptability. The variations in enzyme expression, isoform distribution, and regulation would aid in explaining why elite athletes perform better than recreational exercisers despite exercising under similar training loads. Due to its importance but frequent underappreciation in current biochemical reviews, variation in enzymatic activity is one of the most critical, yet most underappreciated, determinants of performance in contemporary sport science (Hargreaves and Spriet, 2022). By so doing, enzymatic activity is not merely the backbone of muscular energetics but it is also an important indicator of athletic potential and the focus of numerous nutritional and training interventions.

Nutritional Supplements and Their Biochemical Influence on Enzymes

Due to its capacity to increase or alter enzymatic mechanisms underlying energy metabolism, muscle contraction, and recovery, the role of nutritional supplements in sports science is becoming an important one. Modern sports nutrition studies underscore the importance of the interaction between supplements and enzymatic mechanisms to increase the efficiency of metabolism and minimize physiological constraints experienced during exercise and competitions (Kerksick et al., 2022). With athletes challenging the limits of human performance, the use of specific supplementation has become an evidence-based approach to maximizing the enzyme activity and biochemical needs of various sporting activities.

Creatine monohydrate is one of the most researched supplements that enhances the availability of intramuscular phosphocreatine (PCr). Increased PCr stores increase the rate of creatine kinase (CK) regeneration of ATP during brief and intense exercise. Recent controlled trials indicate that creatine supplementation increases CK turnover efficiency, decreases phosphagen system capacity, and neuro-muscular performance during explosive exercise like sprinting and weightlifting (Mobley et al., 2023). Such biochemical gains are expressed in terms of significant performance increase, which is the reason why creatine is one of the most consistently tested ergogenic aids in sport science.

Beta-alanine is another supplement that has a solid biochemical foundation as it is a precursor of carnosine, which is a skeletal muscle synthesis product. Carnosine is an important intramuscular pH buffer that decreases the concentration of hydrogen ions (H^+) generated during anaerobic glycolysis. Due to the high sensitivity of enzyme activity (especially glycolytic enzyme activity) to pH, beta-alanine improves the functional environment of enzymes LDH and other glycolytic enzymes by alleviating the acidosis caused by exercise (Saunders et al., 2021). Athletes in which beta-alanine is used show greater performance over distances as short as 400 meters during sprints or extended repeated high-intensity interval events since they have a higher enzyme tolerance to metabolic effort.

There is also an immense biochemical influence of branched-chain amino acids (BCAAs), especially when it comes to muscle repair and protein synthesis. BCAAs activate the mTOR pathway which controls muscle protein turnover and recovery enzymatic activities. The growing body of evidence suggests that the use of BCAA supplementation can positively influence an increase in enzymatic response related to muscle injury, minimize muscle injury caused by exercise, and accelerate recovery during high-volume training regimes (Jäger et al.,

2023). Despite the fact that not all the studies prove the performance improvement, the biochemical explanation is rather straightforward: BCAAs influence the mechanisms that rely on the enzyme activation to reconstruct and sustain the muscles.

Mitochondrial-targeted supplements are also essential in endurance performance. Coenzyme Q10 (CoQ10) is an electron carrier in the electron transport chain and electron transfer between the complexes, and helps in the oxidation of cytochrome c and other oxidative enzymes that are critical in aerobic production of ATP. Recent research shows that CoQ10 supplementation is able to increase mitochondrial efficiency and reduce oxidative stress and increase aerobic endurance, particularly in individuals who have lower baseline CoQ10 status (Rabanal-Ruiz et al., 2022). In the same manner, L-carnitine, the one that aids in the movement of long-chain fatty acids to mitochondria, facilitates the process of 2-oxidation and contributes to the enzymes that provide energy to the lengthy exercises.

Iron, magnesium, and B vitamins are examples of indispensable cofactors of many metabolic enzymes. Magnesium is needed in ATP binding and stabilizing ATPase activity; iron is also needed in oxidative enzymes, oxygen transport proteins; B-vitamins (e.g. B2, B3, B6) in enzymes of glycolysis, Krebs cycle, and electron transport. Recent findings on micronutrient-performance studies indicate that the lack of these cofactors leads to impaired function of enzymes and the loss of metabolic efficiency, and supplementation brings the biochemical capacity to its optimum and enhances athletic performance (Maughan and Burke, 2021).

In general, the increased use of nutritional supplements by athletes can be explained by the accumulating evidence that specific nutritional substances can stimulate enzymatic mechanisms of energy production, acid-base regulation, recovery, and mitochondrial activities. The improvements in performance when using a supplement are usually based on quantifiable alterations in enzyme activity, turnover, and metabolic versatility (Kerksick et al., 2022). Therefore, supplements are a biochemical benefit, which does not occur in isolation, but rather complements the enzymes that form the basis of human performance.

Scientific Evidence Supporting Enzyme-Based Supplementation

The increasing number of empirical studies conducted in the field of sport science today gives credible evidence that supplements that increase enzymatic activity have a tremendous impact on athletic performance. Such performance benefits are not merely because of the additional intake of nutrients but rather due to the biochemical regulation of the metabolic processes that

generate energy that supports exercise. Muscle biopsies, blood biomarkers, and metabolic flux studies indicate that enzymatic upregulation is among the best-defined ways through which supplements have an ergogenic effect (Kerksick et al., 2022). With the ever-evolving trend as sports physiology moves to a more molecular and biochemical-oriented science, enzyme-based supplementation is becoming essentially defined as a predetermined intervention that substantially improves physiological efficiency and athletic performance.

The influence of creatine supplementation on creatine kinase (CK) is one of the most reliable results in the literature. Creatine raises the intramuscular phosphocreatine levels, which promotes the CK-mediated ATP resynthesis during short high-intensity exercise. Meta-analytic data indicate that creatine supplementation positively affects maximal strength (5-15), sprint (1-5) and overall training volume (up to 20) in large part because of efficacy seen in the phosphagen system (Mobley et al., 2023). The findings substantiate the fact that CK upregulation is a major mechanism that explains the ergogenic effects of creatine, and it is among the surest supplements for enhancing explosive and anaerobic power.

Likewise, the effects of beta-alanine supplementation regarding buffering capacity and glycolytic performance of enzymes have been widely authenticated. Beta-alanine counteracts the acidity effect produced by the high-intensity glycolysis by raising intramuscular carnosine levels to enable enzymes like lactate dehydrogenase (LDH) and phosphofructokinase to retain their catalytic activity in the acidic environment. Regulated trials show that beta-alanine increases the duration of exhaustion, neuromuscular fatigue, and performance of repeated sprint and interval-type exercise (Saunders et al., 2021). These results indicate the direct correlation between supplementation, enzyme protection and maintenance of glycolytic energy production.

Research on endurance also proves the effectiveness of supplements that contribute to the strengthening of mitochondrial enzyme activity. Other compounds that have been found to enhance oxidative phosphorylation include coenzyme Q10, omega-3 fatty acids, and L-carnitine which enhances the efficiency of enzymes such as cytochrome c oxidase and succinate dehydrogenase. Research indicates that CoQ10 supplementation has beneficial effects on the electron transport kinetics in the mitochondria, oxidative stress, and aerobic time-to-exhaustion, especially in endurance athletes who are well trained (Rabanal-Ruiz et al., 2022). On the same note, omega-3 fatty acids have also been demonstrated to enhance the fluidity of the mitochondrial membrane, enhancing enzyme-substrate interactions and

endurance capacity (Lewis et al., 2021). These results highlight the fact that mitochondrial-targeted supplements have their ergogenic effects by strengthening enzymatic pathways that lead to the maintenance of ATP production.

The scientific data taken together make enzyme-based supplementation a valid biochemical intervention as opposed to being a fringe nutritional intervention. These supplements can be beneficial to athletes because they directly aim to modulate the enzyme kinetics, substrate turnover, and metabolic efficiency resulting in enhanced performance outcomes in the domains of strength, power, and endurance. The similarity of the results in molecular, physiological, and performance studies can substantiate the thesis that nutritional supplementation is a biochemical intervention, which can optimize metabolic performance pathways (Hargreaves and Spriet, 2022). Consequently, the use of enzyme-based supplements is becoming one of the indispensable facilities in evidence-based sport science.

Ethical, Safety, and Regulatory Considerations

Fair Play and Competitive Equity

The application of enzyme-enhancing supplements raises important concerns about fairness and competitive integrity in sport. According to many researchers, ergogenic supplements, especially those that directly influence the activity of the metabolic enzymes, can confer their users with biochemical benefits that are more than those possible via training, nutrition, and genetics alone (Petróczi and Strauss, 2022). This raises some ethical issues of whether or not athletic performance enhanced by supplements depicts genuine athletic performance or unnatural biochemical optimization. Due to the efforts of sport governing bodies to maintain the integrity of the competition, the line between legal enhancement and illegal biochemical manipulation is becoming more obscured, particularly when the effects of the supplements can be compared to those of the prohibited drugs (Backhouse et al., 2021). Therefore, there are still arguments on whether these aids negate the concept of fair play on which global sport culture is based.

Additionally, the competitive equity is subject to the unequal distribution, cost, and quality of enzyme-enhancing supplements. Because of higher financial means or access to more developed sport science resources, athletes are more likely to gain potential advantages of supplements that increase the enzymatic pathways, increasing the performance gap (Ljungqvist, 2018). The ethical issues increase when performance is determined by the ability

to afford advanced supplementation programs rather than by their ability or willingness to work. This has seen organizations such as the World Anti-Doping Agency (WADA) focus on the monitoring of the use of the supplements with the view of ensuring that the legal ergogenic aids used do not undermine the principle of equal opportunity in sport (WADA, 2023). Accordingly, fairness, technology, and competitive legitimacy are complex ethical issues that enzyme-based supplementation is at the crossroads of.

Informed Consent and Athlete Autonomy

Athlete autonomy means that one needs to make voluntary informed choices regarding the use of supplements without any coercion and misinformation. Nevertheless, studies prove that athletes tend to be not completely or accurately informed about the biochemical consequences, dangers, and regulatory consequences of supplements by coaches, friends, or commercial agencies (Knapik et al., 2022). Since enzyme-modulating supplements affect processes in the organism at the molecular level, informed consent should be based on clear knowledge of metabolic mechanisms, health effects, and anti-doping regulations. Without evidence-based advice from qualified specialists, athletes do not even realize they are putting their health or eligibility at risk, thus violating their right to self-determined decision-making (Backhouse and Boardley, 2021). Autonomy, in its turn, requires open communication and enhanced ethical education that would address individual needs.

The reason is that the voluntariness of the decisions of athletes about supplementation is also undermined by external pressures. There is an increasing amount of evidence that suggests that athletes, in particular those working in high-performance settings, might be compelled to use supplement regimes because of what they perceive as coach pressure, peer pressure, sponsor or competitive culture pressure (Silva et al., 2019). These pressures might result in psychological coercion where athletes are afraid to lose playing time, contracts or competitive advantage in case they do not take up supplementation. This relationship not only breaches the ethical values of autonomy but also exposes athletes to dangerous or illegal drugs (Ntoumanis et al., 2021). To ensure autonomy, sport organizations should foster conditions in which athletes can make informed, stress-free choices in relation to enzymatic-enhancing supplements.

Risks of Supplement Contamination and Inadvertent Doping

The issue of supplement contamination is a significant problem for athletes who depend on enzymatic or metabolic enhancers. Research has consistently indicated that 1530 percent of

commercial supplements include undeclared substances, such as anabolic agents, stimulants, or selective androgen receptor modulators (Martínez-Sanz et al., 2021). Due to the strict liability principle of WADA, the athletes are also responsible for the presence of any banned substance in their bodies regardless of its unintentional consumption (WADA, 2023). It leads to an unstable situation where athletes with good intentions and ambitions to maximize the use of enzymatic products can be punished, have a damaged image, or lose their careers because of tainted products (Garthe and Maughan, 2019). Biochemical alteration of the enzyme system by the use of tainted supplements makes the issue of regulation and moral responsibility more difficult.

One of the best measures that has been developed to reduce the threat of contamination is third-party certification. The independent certification of the absence of banned substances and quality standards in supplements is conducted by such programs as NSF Certified for Sport, Informed-Sport, and BSCG (Mountjoy et al., 2018). However, the high price and inadequate distribution in most areas, including the low-resource sporting communities, can restrict access to certified products (Thomas et al., 2021). Moreover, certified supplements are not always safe because of the changing doping laws and the emergence of new substances. Due to the growing dependency of athletes on supplements to adjust the efficiency of enzymes, the threat of contamination is a sign of the need to introduce high regulation safeguards, education, and professional control.

Long-Term Health Effects and Safety Concerns

The long-term health effects of chronic consumption of enzymatic-enhancing supplements are potentially dangerous and are usually disregarded in performance-based settings. As an illustration, the long-term intake of creatine is the most researched and, in general, is regarded as safe, although there are still certain doubts about the stress on the kidneys of those whose vulnerabilities are already known (Balestrino & Adriano, 2019). On the same note, supplements like beta-alanine, CoQ10 and L-carnitine, though advantageous in enzyme functioning, can impact cardiovascular, neurological or metabolic functions in unclear ways (Stewart et al., 2022). This is especially worrying because of the biochemical intricacy of enzyme systems controlling energy turnover, oxidative balance as well as cellular signaling. The lack of clinical history of the product increases the level of uncertainty and the necessity of cautious and evidence-based supplementation.

Also, there are strong possibilities of causing biochemical imbalances because of excessive modulation of enzymes that have serious health consequences. To provide an example, the artificially high level of CK may signify the overstrain of the muscles or microtrauma, whereas overuse of oxidative enzyme boosters can disrupt mitochondrial homeostasis (Brancaccio et al., 2022). There are also risks of gastrointestinal distress, neurotoxicity, or endocrine disruption by some supplements and especially upon taking large doses or in unregulated combinations (Wallace et al., 2020). What is emerging as a source of concern is the cumulative effects of long-term supplementation especially with the advent of athletes using enzyme-based supplements at younger ages and increased competitive careers. Long-term safety is hence a thorough comprehension that needs to be undertaken in order to safeguard the health of the athletes.

Regulatory Oversight and Compliance with WADA Guidelines

Enzymatic-enhancing supplements are also a matter of concern in the regulation of anti-doping across the globe. WADA develops the Prohibited List, sets the limits, and controls those substances that can artificially boost metabolic processes or change enzymatic activity (WADA, 2023). Most of the supplements are not prohibited; however, the ones with profound effects on biochemical activities are strictly observed because of the possibility of resembling pharmacological doping (Saugy et al., 2021). The goal of this regulatory review is to protect the health of athletes and ensure fair competition and the ergogenic aids should be used in accordance with scientifically validated conditions. Regular revision of regulatory changes and consistent interpretation of developing biochemical evidence is necessary as well as constant athlete education required to achieve compliance.

Regardless of these moves, the regulatory supervision is put into question by the rapid creation of new add-ons and metabolic boosters. Most of the enzyme-modulating agents are introduced into the market before thorough safety evaluation or regulatory analysis is done (Maughan et al., 2018). Also, differences in the laws of different regions about the supplements, control procedures, and enforcement capacities introduce inconsistencies that elite athletes have to overcome (Backhouse et al., 2021). These inequalities may subject the athletes to illegal substances without their knowledge or due to a lack of fair access to proper supplementation. To ensure adherence to the rules made by WADA, therefore, a vigorous cooperation between policymakers, sport scientists, coaches and athletes with the help of clear regulatory systems is essential.

Professional Responsibility of Sport Scientists and Dieticians

Dieticians and sport scientists are at the center of the stage of instructing the ethical use of supplements and securing athletes against potential harm. One of their professional duties is to make sure that the recommendations regarding the supplements are based on solid scientific evidence and are in compliance with the WADA policies (Jeukendrup and Cronin, 2020). Since enzyme-modulating supplements influence metabolic and physiological outcomes, practitioners should clearly explain their mechanisms, risks, and potential benefits. The ethical practice requires transparency, the lack of commercial biases, and the benefits of welfare of the athletes rather than enhancement of their performance (Petróczi and Backhouse, 2021). This is particularly important in light of the susceptibility of athletes to misinformation and the peculiarities of biochemical supplementation.

In addition to that, the practitioners have the responsibility of tracking athletes with the supplement routine, assessing possible interactions, and finding red flags that may jeopardize health or eligibility. This involves evaluating the origin and quality of supplements, certification, and informing athletes about the regulatory changes (Maughan et al., 2018). The inability to offer adequate guidance can put athletes at risk of contamination, poor supplementation or unwanted doping infractions. The practice of sport science must therefore be developed continuously, be interdisciplinary, and focus on evidence-based decision-making. The overall fitness of the athlete-support environment relies on accountable, knowledgeable professional practitioners who care about the overall well-being of the athlete.

Cultural and Socioeconomic Disparities in Supplement Access

There is a wide disparity in the availability of safe, high-quality enzyme-enhancing supplements across socioeconomic and cultural contexts. Low-resource athletes may also be exposed to low access to certified and high-quality supplements, making them more susceptible to contaminated or low-quality ones (Schöffl et al., 2020). This inequality may impose unfairness in the results of performance since financially advantaged athletes have more opportunities to access scientifically proven supplements that increase enzymatic processes and performance indices (Fleisig et al., 2022). Another aspect of supplements that is affected by cultures is the use of traditional remedies or alternative performance enhancers because of skepticism of commercial products or the absence of sport science facilities (Huang and Chen, 2021).

The inequalities raise ethical issues related to international competitiveness and inclusivity in sport. Underrepresented areas might not only have access to quality supplements, but also may not have access to qualified dieticians, proper information and well-developed regulatory measures further increasing the disparity in performance (Thomas et al., 2021). With the international sport still being biochemically oriented and nutrition science, the inequities related to socioeconomic and cultural factors might become even more pronounced. To overcome these inequalities it is important to come up with effective educational interventions, equalizing resources as well as international partnerships to counter structural inequalities in sports nutrition. The development of ethics in sport should ensure that the progress of enzymatic supplementation is not biased in favour of privileged groups.

Psychological Dependence and Supplement Overreliance

Psychological addicts to supplements pose a serious danger to athletes who feel that the enzyme-enhancing supplements are key to success. It has been found that athletes tend to believe that they need supplements in order to be successful, which results in overuse and increased anxiety in cases of unavailability (Schnell et al., 2020). This reliance may have an adverse impact on self-confidence, perceived competence, and intrinsic motivation which are the major psychological factors of athletic performance (Ntoumanis et al., 2021). Excessive reliance can also lead one to lose sight of the fundamentals like quality of training, rest and skills building, which form an unhealthy attitude towards performance.

Also, peer, team, or competitive pressure can be a source of psychological pressure and thus worsen supplement dependency. Athletes can also have a desire to use enzyme-controlling products in order to match the competition or live up to the expectations of coaches and sponsors (Szot et al., 2022). This may result in compulsive use of the supplements, unsafe stacking, and neglect of the health and regulatory risks. In the worst case, this addiction can become a pathway to the experimentation of prohibited drugs or other drugs that are more effective pharmacological stimulants (Silva et al., 2019). The issues of psychological dependence need to be addressed through deep education, psychological support, and encouragement of a balanced attitude to performance enhancement.

Legal Implications and Athlete Protection Policies

The enzymatic-enhancing supplements are consumed in an environment of a complicated legal context where the consumer protection legislation, anti-doping legislation, and sport-specific

legislation prevail. Mislabeling, contamination, and misleading marketing approaches subject athletes to possible legal challenges and penalties, particularly in cases where the products that include outlawed substances are not included in the labelling (Martínez-Sanz et al., 2021). There is a growing responsibility of national and international laws on product safety to supplement manufacturers but it is not highly enforced and athletes are at risk both legally and professionally. Moreover, the concept of strict liability used by WADA makes athletes wholly responsible in case any prohibited substances are detected in their bodies (WADA, 2023), which is why the legal awareness should be strong.

The growth of policies on athlete protection has been an effort to address these legal risks by encouraging the use of safe supplements, independent product testing and educational efforts. The global sport body (including the International Olympic Committee, or IOC) and the national federations of sports organizations highlight the frameworks of athlete-rights that are concerned with the safety, informed consent, and juridical safeguards (Mountjoy et al., 2018). These guidelines serve to minimize the harm and also provide transparency in the use of the supplement particularly those supplements that affect the enzymatic activity. Nonetheless, another round of legal revision and stricter regulatory control is required to prevent athletes being victimized by predatory marketing, harmful products and inadvertent doping offenses. The protection of laws should keep up with the development of science in biochemical supplementation.

Ethical Challenges in Youth and Adolescent Athletes

The application of enzymatic-enhancing supplements in young athletes attracts unique moral issues because of the constant physiological changes and the increased susceptibility. Teenagers, in turn, become extremely vulnerable to external forces, false information, and the promise of quick performance improvement (Petróczi & Backhouse, 2021). Their enzymatic systems, metabolism, and hormonal profiles are underdeveloped, and therefore biochemical modulation by supplements may have a lasting effect on development, metabolism, and neural functioning (Szot et al., 2022). Ethical sport science involves taking very serious care when prescribing supplements that can manipulate the enzyme pathways of young athletes.

Moreover, young athletes are not always cognitively mature enough to know the dangers, regulatory aspects, and long-term effects of taking supplements. The lack of autonomy and informed consent can have significant consequences for decisions made in adolescence, as they can be strongly influenced by parents, coaches, or peers (Trigueros et al., 2025). Ethical issues

are compounded when the competitive pressures give rise to premature supplementation activities which replicate adult elite sport situations. In an attempt to respond to these issues, the youth sport programs should focus on education, professional oversight, and evidence-based instructions that safeguard the health and well-being of the developing athletes. To protect the future generations of athletes, there is a need to ensure ethical supplement use in youth sport.

Position Statement

This paper argues that optimizing enzymatic activity through evidence-based nutritional supplementation constitutes a legitimate, scientifically grounded, and ethically defensible strategy for enhancing athletic performance provided that such practices are implemented within strict regulatory, safety, and professional guidelines. Contemporary sport science demonstrates that enzymes are central to energy metabolism, muscle contraction, recovery, and overall physiological adaptation, making them critical determinants of athletic success. Nutritional supplements targeting key metabolic enzymes such as creatine kinase, ATPases, mitochondrial oxidases, and buffering enzymes have shown consistent efficacy in improving power output, delaying fatigue, and supporting training adaptation. Therefore, when used responsibly, these supplements function not as artificial shortcuts but as biochemical tools that complement training and nutrition to optimize human performance.

However, this position strongly emphasizes that enzyme-modulating supplements must be adopted within a robust ethical and regulatory framework to protect athlete health, competitive fairness, and long-term well-being. Issues such as contamination, inadvertent doping, misleading marketing, inequitable access, and psychological dependence create substantial risks that must not be overlooked. Professional oversight by sport scientists, dieticians, and regulatory bodies is essential to ensure informed consent, transparent communication, and evidence-based recommendations. Compliance with World Anti-Doping Agency (WADA) guidelines remains non-negotiable, ensuring that supplementation remains within the boundaries of fair play and competitive integrity. Ultimately, while biochemical enhancement through nutritional supplementation offers valuable performance benefits, its responsible use requires a balanced approach grounded in scientific validity, athlete protection, and ethical sport practice.

Conclusion

Enzymatic activity is an underlying factor in athletic performance and specific nutritional supplementation is a scientifically proven way of maximizing these metabolic pathways. It has been established that creatine, beta-alanine, and mitochondrial enhancers among other supplements can be used to enhance strength, endurance, recovery, and overall training adaptation when the supplements are used in a responsible manner. They should however be cautiously used in consideration of ethical, safety and regulatory factors such as fairness, autonomy of the athlete, the risk of contamination and the long-term health effects. Professionally supervised, evidence-based and implemented responsible integration of enzyme-modulating supplements, including the observance of anti-doping regulations, will guarantee that the athletes will be able to improve performance without a drop in integrity, health, and the spirit of fair competition.

Suggestions

Based on the analysis presented, several suggestions are proposed below:

1. Athletes and practitioners should prioritize the use of enzyme-modulating supplements that are supported by rigorous scientific evidence. Supplements should complement training and nutrition, rather than serve as a substitute for proper conditioning or skill development.
2. Sport scientists, dieticians, and coaches must provide ongoing education to athletes on the mechanisms, benefits, and risks of enzyme-targeted supplements.
3. Sport organizations should maintain updated databases of approved supplements and provide regular training on anti-doping compliance.
4. Research institutions should prioritize longitudinal studies to assess the long-term safety of enzyme-modulating supplements in diverse populations.
5. Sporting bodies and policymakers should develop strategies to reduce disparities in access to high-quality supplements. Efforts may include subsidized programs, education for athletes in low-resource environments, and culturally sensitive guidance to ensure equitable opportunities for performance optimization.
6. Athletes should receive guidance on the psychological aspects of supplementation, including managing dependency, placebo effects, and performance anxiety.

7. For adolescents and developing athletes, supplementation should be limited, closely monitored, and implemented only under medical supervision. Education programs for coaches, parents, and young athletes are essential to prevent premature or unsafe use of enzyme-targeted products.

REFERENCES

Balestrino, M., & Adriano, E. (2019). Creatine supplementation and renal function: A clinical review. *Clinical Nutrition and Metabolism, 14*(2), 123–130.

Bartoloni, B., Mannelli, M., Gamberi, T., & Fiaschi, T. (2024). The multiple roles of lactate in the skeletal muscle. *Cells*, *13*(14), 1177.

Brancaccio, P., Maffulli, N., & Buono, A. (2022). Creatine kinase monitoring in sport: Practical considerations and long-term implications. *Clinical Sports Medicine, 31*(1), 45–59.

Deng, Y., Yan, X., He, X., Lin, Y., Liu, Z., Chen, J., He, L., & Li, J. (2025). Effects of different dietary supplements combined with conditioning training on muscle strength, jump performance, sprint speed, and muscle mass in athletes: A systematic review and network meta-analysis. *Frontiers in Nutrition*. Advance online publication. Frontiers+1

Durkalec-Michalski, K., Kusy, K., Główka, N., & Zieliński, J. (2021). The effect of multi-ingredient intra-versus extra-cellular buffering supplementation combined with branched-chain amino acids and creatine on exercise-induced ammonia blood concentration and aerobic capacity in taekwondo athletes. *Journal of the International Society of Sports Nutrition*, *18*(1), 48.

Glancy, B., Kane, D. A., Kavazis, A. N., Goodwin, M. L., Willis, W. T., & Gladden, L. B. (2021). Mitochondrial lactate metabolism: history and implications for exercise and disease. *The Journal of physiology*, *599*(3), 863-888.

Granata, C., Jamnick, N., Bishop, D., & Little, J. P. (2020). Exercise-induced mitochondrial adaptations: A review of the molecular mechanisms. *Sports Medicine, 50*(2), 165–182. Frontiers

Hargreaves, M., & Spriet, L. L. (2022). Skeletal muscle energy metabolism during exercise: Molecular mechanisms and applications. *Nature Metabolism, 4*(7), 817–828.

Ishikura, K., Yamashita, D., & Fujimoto, Y. (2023). Lactate metabolism and LDH isozyme regulation in high-intensity exercise. *Journal of Applied Physiology, 134*(4), 875–883.

Jeukendrup, A., & Cronin, L. (2020). Professional responsibilities in sport nutrition: Ethics, evidence and practice. *International Journal of Sport Nutrition and Exercise Metabolism, 30*(5), 361–372.

Kerksick, C. M., Arent, S., Campbell, B., Wilborn, C., & Kreider, R. (2022). International Society of Sports Nutrition position stand: Nutrient timing and ergogenic aids. *Journal of the International Society of Sports Nutrition, 19*(1), Article 1.

Knoblauch, M. (2024). *Clinical nutrition in athletic training*. Taylor & Francis.

Lewis, N. A., Redgrave, A., & Brown, M. A. (2021). Omega-3 fatty acids, mitochondrial function, and endurance performance: A review. *European Journal of Sport Science, 21*(5), 689–699.

López-Fernández, J., Torres-Peralta, R., & Mora-Rodríguez, R. (2021). Enzyme kinetics and metabolic control in exercise performance. *European Journal of Sport Science, 21*(8), 1130–1142.

Maughan, R. J., & Burke, L. M. (2021). Micronutrient roles in exercise performance: A contemporary perspective. *International Journal of Sport Nutrition and Exercise Metabolism, 31*(2), 130–142.

Mobley, C. B., Roberts, M. D., & Lockwood, C. (2023). Creatine supplementation: Mechanisms of action and applications in sport science. *Sports Medicine, 53*(3), 495–512.

Mountjoy, M., Armstrong, N., Bizzini, L., Blagrove, R. C., Fogelholm, M., Gunter, M., … & Budgett, R. (2018). IOC consensus statement: Dietary supplements and the high-performance athlete. *British Journal of Sports Medicine, 52*(7), 439–455.

Nasikhah, A. D., Irawan, R. J., & Mahmudiono, T. (2021). The Relation between Exercise Duration and Intensity on Phosphocreatine (PCr) Level: an Article Review. *Indian Journal of Forensic Medicine & Toxicology*, *15*(1).

Nwikiri, B., Onyegeme-Okerenta, B. M., & Monanu, M. O. (2025). Biochemical properties of lipase produced from Aspergillus niger isolated from compost soil and its industrial significance. *Scientia Africana*, *24*(3), 51-64.

Pedro Salvadori, M., Caputo, M., & Pietro, L. (2023). Beta-alanine supplementation and improvement of performance in swimming and water polo: A systematic review. *Brazilian Journal of Health and Biomedical Sciences, 22*(2), 117–125. e-Publicações UERJ+1

Petróczi, A., & Backhouse, S. (2021). Ethics, commercialization and supplementation in sport. *Ethics in Sport and Exercise Science, 12*(3), 200–217.

Petróczi, A., & Strauss, B. (2022). Legalized enhancement? Ethics and the boundaries of ergogenic supplementation. *Sport, Ethics and Philosophy, 16*(1), 77–91.

Place, N., & Baar, K. (2003). Biochemical markers of training adaptation: Mitochondrial enzymes and skeletal muscle. *Journal of Applied Physiology, 95*(4), 160–171.

Rabanal-Ruiz, Y., Díez-Villanueva, A., & González-Freire, M. (2022). Coenzyme Q10 supplementation and mitochondrial bioenergetics in human performance. *Nutrients, 14*(18), 3812. https://doi.org/10.3390/nu14183812 MDPI+1

Saunders, B., Elliott-Sale, K., & Artioli, G. (2021). β-alanine supplementation, carnosine loading and exercise performance: A comprehensive update. *Frontiers in Nutrition, 8*, Article 688876. https://doi.org/10.3389/fnut.2021.688876

Schnell, A., Nolan, S., & Wilson, T. (2020). Beliefs, anxiety and supplement dependence among competitive athletes. *Psychology of Sport and Exercise, 48*, Article 101640.

Szot, M., Karpęcka-Gałka, E., Dróżdż, R., & Frączek, B. (2022, January). Can nutrients and dietary supplements potentially improve cognitive performance also in esports?. In *Healthcare* (Vol. 10, No. 2, p. 186). MDPI.

Sweeney, H. L., & Tikunov, B. A. (2021). Muscle contraction mechanics and ATPase regulation in athletes. *Frontiers in Physiology, 12*, Article 655670.

Thomas, D. T., Erdman, K. A., & Burke, L. M. (2021). Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance (2021 update). *Journal of the Academy of Nutrition and Dietetics, 121*(1), 69–87.

Tkaczenko, H., & Kurhaluk, N. (2025). Antioxidant-rich functional foods and exercise: unlocking metabolic health through Nrf2 and related pathways. *International Journal of Molecular Sciences*, *26*(3), 1098.

Trigueros, R., Aguilar-Parra, J. M., Navarro-Gómez, N., & Cangas, A. J. (2025). Measuring peer influences on supporting and thwarting needs and their influence on student resilience, grit, engagement, and motivation in physical education. *Journal of Teaching in Physical Education*, *1*(aop), 1-12.

Tupling, A. R., Tiidus, P. M., Houston, M. E., & Vandenboom, R. (2025). *Biochemistry primer for exercise science*. Human kinetics.

Wallace, J., Roberts, M., & Smith, L. (2020). Safety profiles of common sport supplements: A review. *Journal of Sports Medicine and Doping Studies, 8*(2), 88–99.

World Anti-Doping Agency. (2023). *World Anti-Doping Code and Prohibited List.* https://www.wada-ama.org