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Nutritional Ergogenic Aids for Optimizing Post-Exercise Recovery in Athletes: A Review Article

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Abstract
Effective post-exercise recovery is essential for athletic performance and long-term training adaptation. This review systematically explores the role of key nutritional ergogenic aids-Branched-Chain Amino Acids (BCAAs), L-citrulline malate (CM), glutamine, creatine, and omega-3 fatty acids-in accelerating recovery by reducing muscle damage, oxidative stress, and inflammation. BCAAs and creatine emerged as the most consistently effective, promoting muscle repair and reducing soreness through mTOR activation and anti-inflammatory action. Glutamine and CM demonstrated conditional benefits, particularly in immune support and perceived exertion reduction, respectively. Omega-3 fatty acids showed potential in mitigating systemic inflammation and cellular damage. The variability in outcomes emphasizes the importance of individual response, dosing strategies, and timing. Despite promising findings, gaps persist in understanding long-term adaptations and synergistic effects of multi-nutrient protocols. This review highlights the need for personalized, evidence-based supplementation frameworks to optimize athletic recovery and performance.

Keywords: BCAA, creatine, glutamine, omega-3 fatty acids, citrulline malate, recovery, supplementation

1. Introduction

Recovery plays a crucial role in sports by helping player restore their physical and physiological state after intense matches or training sessions. Effective recovery strategies can enhance performance, reduce muscle damage and inflammation, and minimize the risk of injuries. (Altarriba-Bartes et al., 2020; Coelho et al., 2021; Silva et al., 2018). Post-exercise recovery involves a complex interplay of muscle damage, inflammation, and oxidative stress, with markers like CK and IL-6 providing insight into the recovery timeline. (Ascensão et al., 2008; Ispirlidis et al., 2008; Silva et al., 2018). Complete recovery of muscle function biochemical markers may take up to 72 hours or longer, depending on the intensity of the match and individual player characteristics. (Moya-Amaya et al., 2021). These markers, blood lactate, and increased heart rate highlighted the need for tailored recovery strategies to manage fatigue and optimize performance in subsequent training and matches. Several recovery methods have been studied for their effectiveness in promoting recovery among athletes. However, apart from different recovery methods, proper sleep, and nutrition, modern-day supplementation plays a crucial role in recovery by providing the necessary nutrients to repair tissue, replenish energy stored, reduce inflammation, and support overall physical and mental well-being.

2. Methodology

To ensure the scientific rigor and validity of this review, a comprehensive and structured literature search was systematically conducted utilizing PubMed, Scopus, and Google Scholar databases. The search strategy employed Boolean combinations of relevant terms, including "post-exercise recovery," "ergogenic aids," "BCAA," "creatine," "glutamine," "omega-3 fatty acids," "citrulline malate," and "muscle soreness," to capture all pertinent literature. Studies were included if they were peer-reviewed articles published in English, involved human participants classified as athletes or physically active individuals, and comprised randomized controlled trials (RCTs), meta-analyses, or systematic reviews. Exclusion criteria encompassed animal studies (unless providing mechanistic insights not yet demonstrated in humans), research not evaluating recovery-related biomarkers or performance metrics, and single-case reports.

3. Results

Nutritional intervention for recovery

Modern approaches to sports nutrition aim to provide sources of ergogenic aids, which help increase energy production, promote faster recovery, and improve athletes' field performances. (Duttagupta et al., 2024). Nutrition plays a pivotal role in the recovery of athletes after intense training and matches; Numerous strategies have been investigated in the field of sports nutrition to improve players' recovery. The science of recovery has advanced significantly, from the well-established benefits of protein supplements and carbohydrate loading to the use of antioxidants like tart cherry juice and omega-3 fatty acids. However, despite this advancement, a vast landscape of untapped potential remains. Among the promising nutritional interventions are:

3.1 Branched-chain amino acids (BCAAs)

Among the nine essential amino acids for humans (Tsuchiya et al., 2022). Branched-chain amino acids (BCAAs) are three essential amino acids: leucine, isoleucine, and valine (Salem *et al*., 2024). BCAAs are described as having a branched-chain structure (Amawi et al., 2024). They make up approximately 50% of essential amino acids in food and account for 35% to 40% of the total content of essential amino acids in muscle proteins. (Cruzat et al., 2014). These amino acids are unique because they are primarily metabolized in skeletal muscle rather than the liver, allowing them to play a significant role in muscle metabolism and recovery. BCAAs cannot be synthesized by the body as essential nutrients, necessitating their intake through diet or supplements, particularly for athletes engaged in intense physical training. (Salem et al., 2024).

3.1.1 Proposed mechanism

BCAAs have analgesic properties, may inhibit muscle protein breakdown, and enhance muscle protein synthesis, particularly leucine, which has a direct anabolic effect by stimulating the mTOR pathway. Keeping the free muscle amino acid pool high with BCAA supplementation might suppress the signal for muscle protein breakdown or speed recovery. BCAAs may also promote the recovery process of modified muscle tissues induced by mechanical strain and inflammation. They might modulate inflammation (Calder, 2006; Duttagupta et al., 2024; Holeček, 2018; Marquez, 2022).

3.1.2 Role in recovery

Research, including a study on young soccer players, suggests that BCAA supplementation may help reduce markers of muscle damage (CK) and inflammation (Hs-CRP) following acute resistance exercise (Atashak & Baturak, 2012). Other studies in soccer players found no significant effect of BCAA on muscle damage markers (CK, LDH) (Aminiaghdam et al., 2012) or recovery rates (Ahmet Mor et al., 2021). General research indicates BCAAs are likely helpful in reducing muscle soreness and CK levels, possibly through mechanisms involving protein synthesis and modulation of inflammation. (Ahmet Mor et al., 2021; Aminiaghdam et al., 2012; Cruzat et al., 2014; Nicastro et al., 2012; Salem et al., 2024).

3.2 L-Citrulline Malate

Citrulline malate (CM) is a popular dietary supplement among athletes, composed of the non-essential amino acid L-citrulline and malic acid. L-citrulline is primarily found in watermelon, while malic acid is common to apples and grapes. CM was initially used as a pharmaceutical drug to treat patients with asthenia to reduce recovery time after physical activity. Athletes' pursuit of competitive benefits has led to CM being fundamentally considered a potential ergogenic supplement. (Aguayo et al., 2021; Cunniffe et al., 2016; Gough et al., 2021).

3.2.1 Proposed Mechanism

The potential use of citrulline supplements to relieve fatigue or muscle soreness is based on several hypothetical mechanisms. The proposed ergogenic mechanisms of CM include improved ammonia metabolism, lactate buffering capacity, increased vasodilation via increased nitric oxide (NO), and increased production of adenosine triphosphate (ATP) (Burgos et al., 2025; Chappell et al., 2024; Rhim et al., 2020).

3.2.2 Role in Recovery

Based on the sources, L-Citrulline malate (CM) shows mixed results for post-exercise recovery. (Burgos et al., 2025). It has been reported to significantly reduce perceived exertion and muscle soreness at 24 and 48 hours after exercise. (Rhim et al., 2020). One study noted a 40% decrease in muscle soreness at 1 and 2 days post-training (Divito et al., 2022). However, some research indicates CM does not improve muscle recovery after resistance exercise in untrained individuals. Evidence for effects on muscle damage and inflammatory markers in humans is also varied; a study in soccer players found no significant changes in LDH or CK levels compared to placebo. (Mirenayat et al., 2024). In mice, L-citrulline potentially prevents skeletal muscle damage by influencing markers like TNNI2, NOX2, NF-κB, HSP-70, IL-6, and caspase 3 (Ghozali et al., 2023). Proposed mechanisms include improving ammonia clearance. (Farney et al., 2019). Increasing Nitric Oxide production via L-arginine to enhance blood flow and muscle regeneration, and ATP production via malate. Antioxidant and anti-inflammatory effects are also suggested. (Gough et al., 2021; Łukaszewicz et al., 2024; Nandyantami et al., 2024; Vårvik et al., 2021).

3.3 Glutamine

Glutamine is one of the most abundant amino acids in the organism, found extensively in human skeletal muscles and blood plasma. It is synthesised by skeletal muscle and other tissues, including branched-chain amino acids. It is considered essential for proper immune function, supplying energy for nucleotide biosynthesis and serving as a fuel for immune cells. Glutamine also functions as a fuel in muscles, a nitrogen precursor, and maintains acid-base balance. Reduced plasma glutamine levels have been observed after sustained or exhaustive exercise and in overtrained athletes, which is linked to impaired immune function. (Córdova-Martínez et al., 2021; Koo et al., 2014; Nicastro et al., 2012).

3.3.1 Proposed Mechanism

A proposed mechanism suggests that branched-chain amino acids (BCAAs) influence skeletal muscle inflammation by modulating glutamine synthesis. This occurs through BCAA transamination, producing glutamate from alpha-ketoglutarate, which glutamine synthetase converts to glutamine. Glutamine transport via System A is sodium-dependent and linked to leucine entry (System L), where leucine entry requires glutamine exit. Increased glutamine requirements, like in catabolic states, could reduce intracellular glutamine and impair leucine transport. (Nicastro et al., 2012).

3.3.2 Role in Recovery
Glutamine is essential for proper immune function and acts as a fuel for immune cells and repair processes. Intense or exhaustive exercise can lead to reduced plasma glutamine levels, which are associated with impaired immune function and potentially reduced protein synthesis. Glutamine supplementation has shown positive effects on decreasing fatigue factor stimulation during recovery from maximal exercise. It may help attenuate markers of exercise-induced muscle damage. Maintaining adequate glutamine levels is essential for supporting immune function and muscle repair post-exercise (Córdova-Martínez et al., 2021; Koo et al., 2014).

3.4 Creatine
Creatine supplementation is well-known for its effects on performance due to increasing intramuscular phosphocreatine (PCr) levels, which aid ATP resynthesis during high-intensity activity. (Forbes et al., 2023; Wax et al., 2021). It is also discussed in the context of recovery.

3.4.1 Proposed mechanism
Creatine has antioxidant capabilities and anti-inflammatory effects following exercise. (Cordingley et al., 2022; Forbes et al., 2023). Pre-race creatine supplementation reduced the rise in inflammatory markers like prostaglandin-E2 (PGE2), tumour necrosis factor-alpha (TNF-alpha), and the muscle damage marker CK in runners. (Forbes et al., 2023). In young soccer players (mean age: 20 years), creatine supplementation (0.3 g/kg/day for 7 days) attenuated the rise in TNF-alpha and C-reactive protein. (Forbes et al., 2023). Creatine supplementation may reduce post-exercise inflammatory response, thereby attenuating markers of muscle damage and soreness. (Wax et al., 2021). However, some studies have reported that creatine supplementation did not reduce muscle damage or enhance recovery. (Greer et al., 2007; Jiaming & Rahimi, 2021). Creatine may be efficacious as a therapeutic intervention following an injury or during periods of limb immobilisation. (Wax et al., 2021).

3.4.2 Role in recovery
Creatine supplementation may accelerate post-exercise recovery (Forbes et al., 2023; Wax et al., 2021), and augment recoverability between bouts of intermittent activity, relevant for sports like soccer (Wax et al., 2021). It has been shown to enhance muscle force recovery after eccentrically induced muscle damage. (Amawi et al., 2024; Cooke et al., 2010; Greer et al., 2007). Creatine may act as a co-regulator or direct manipulator of gene transcription of amino acid pools, potentially enhancing myofibrillar protein synthesis during recovery. (Cooke et al., 2009). It has also been shown to amplify the training-induced increase in satellite cell number and myonuclear concentration, potentially aiding muscle regeneration.

3.5 Omega 3 Fatty Acid
Supplementation with omega-3 fatty acids may attenuate inflammatory markers after eccentric exercise. Specifically, EPA-rich fish oil was shown to partially protect against muscular damage in one study, while fish oil might reduce oxidative stress but not muscle soreness. (Tsuchiya et al., 2022). Omega-3 fatty acids are widely studied for their potential benefits in recovery from physical injury, exercise, and certain diseases, largely due to their anti-inflammatory and antioxidant properties. Research explores their effects on muscle repair, neurological recovery, immune modulation, and overall health, but findings are sometimes inconsistent and optimal dosing remains unclear.

3.5.1 Role in Recovery
Supplementation can reduce muscle damage, inflammation, and oxidative stress after exercise, though results for muscle soreness and performance are mixed. Benefits are more consistent for reducing blood markers of muscle damage and inflammation (Fernández-Lázaro et al., 2024; Nasir & Rahimi, 2024; Xin & Eshaghi, 2021). In acute lung injury, omega-3s improve respiratory function and reduce ICU stay duration (Huang et al., 2020). In cancer and metabolic diseases, they may help regulate inflammation and support recovery (Albracht-Schulte et al., 2018; Wibowo & Willyanto, 2024).

3.5.2 Proposed mechanism
Anti-inflammatory properties of Omega-3s, especially EPA and DHA, reduce the production of pro inflammatory cytokines (e.g., IL-6, TNF-α, CRP) and inhibit NF-κB activation, shifting the body's response from inflammation toward resolution and tissue repair (Fernández-Lázaro et al., 2024; Nasir & Rahimi, 2024; R. Poggioli, K. Hirani, V.G. Jogani, C. Ricordi, 2023). They help stabilize cell membranes, reducing muscle damage markers like creatine kinase (CK), lactate dehydrogenase (LDH), and myoglobin after exercise or injury (Xin & Eshaghi, 2021). It also modulates immune cell function and gene expression, enhancing immune responses and reducing chronic inflammation.

Table 1: Summary of Mechanisms, Biomarker Effects, Recovery Outcomes, and Use Cases of Nutritional Ergogenic Aids

Supplements	Mechanism of action	Biomarkers affected	Recovery outcomes	Effective dosage	Best use cases
BCAAs	Activate mTOR, ↓ MPB, ↓Inflammation	↓ CK, CRP, LDH	↓ Muscle soreness, ↓ muscle damage	5-10 g pre/post exercise	Resistance training, DOMS
Creatine	↑ PCr, ↓ TNF-α, antioxidant properties	TNF-α, CRP, CK	↑ strength recovery ↓Inflammation	0.3g/kg/day (loading), 3-5g/day	Explosive sports, eccentric damage
Glutamine	Immune support, ↓ fatigue	IL-6, CRP, Glutamine plasma level	↓ infections/fatigue	5-10 g/day	Overtraining recovery, immune support
L-Citrulline	↑ NO Production, ↑ ATP, ↓ ammonia	CK, LDH, blood Lactate	↓ perceived fatigue	6-8g/day	Reducing DOMS, endurance buffering
Omega-3s	Anti-inflammatory, membrane stability	IL-6, CK, Oxidtive stress	↓ inflammation	1-3 g/day EPA+DHA	Joint inflammation, systemic recovery

4. Discussion

This review highlights the role of key nutritional ergogenic aids-BCAAs, creatine, L-citrulline malate, glutamine, and omega-3 fatty acids-in supporting post-exercise recovery through various physiological mechanisms. The evidence supports BCAAs and creatine as the most consistent interventions, primarily by reducing muscle protein breakdown, enhancing protein synthesis, and attenuating inflammation. Creatine demonstrates robust benefits in accelerating muscle recovery, reducing inflammatory cytokines (e.g., TNF-α, CRP), and improving ATP resynthesis. BCAAs, especially leucine, aid muscle repair via mTOR activation but show mixed results on markers like CK and LDH, likely due to differences in formulation and dosage across studies. L-citrulline malate may reduce perceived soreness and fatigue through improved nitric oxide production and lactate clearance, though its effects on muscle damage biomarkers remain inconsistent. Glutamine appears valuable in maintaining immune function and reducing fatigue, especially in endurance or overtrained athletes, but its direct recovery benefits are less defined. Omega-3 fatty acids consistently reduce inflammation and oxidative stress, yet their impact on soreness or performance remains inconclusive, suggesting a stronger systemic rather than muscular role in recovery. Overall, outcomes are influenced by supplementation timing, dosage, training status, and individual variability. Future research should prioritize synergistic supplement strategies, sex-specific responses, and long-term adaptations to guide more personalized recovery protocols.

5. Conclusion

Nutritional ergogenic aids, particularly creatine and BCAAs, offer scientifically validated benefits for post-exercise recovery by attenuating muscle damage, inflammation, and oxidative stress. While CM and glutamine show context-dependent efficacy, optimal outcomes depend on nutrient timing, dosage, and athlete-specific factors. Emerging evidence highlights the synergistic potential of multi-nutrient formulations, though mechanistic clarity remains limited. Practitioners should prioritize evidence-based, individualized supplementation strategies aligned with training demands. Further research is warranted to elucidate long-term adaptations and refine protocols for diverse athletic populations.

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