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Exercise Recovery and Athletic Adaptation: The Role of Nutrition and Supplementation in Physically Active Individuals

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Abstract

Purpose of the study:

The aim of this literature-based review was to evaluate current evidence regarding nutritional and supplementation strategies supporting exercise recovery, training adaptation, and athletic performance in physically active individuals and athletes. Particular emphasis was placed on the role of macronutrient intake, functional foods, and evidence-based dietary supplementation in optimizing post-exercise physiological recovery processes.

Materials and methods:

A structured literature search was conducted using PubMed, Scopus, and Google Scholar databases, including studies published up to 2025. The review included systematic reviews, meta-analyses, randomized controlled trials, and narrative reviews investigating nutritional interventions associated with post-exercise recovery, exercise-induced muscle damage, inflammation, glycogen resynthesis, and sports performance. The study selection process was based on the PICOS framework to ensure methodological consistency and relevance of the analyzed literature. Data from eligible studies were synthesized qualitatively with emphasis on practical applications in athletic populations.

Results:
The reviewed evidence demonstrates that nutritional interventions play a significant role in supporting exercise recovery and improving performance-related outcomes. Adequate protein intake was identified as essential for muscle protein synthesis, tissue repair, and training adaptation, while carbohydrate intake was crucial for glycogen restoration and maintenance of exercise capacity. Functional foods rich in polyphenols, including tart cherry products and berries, demonstrated beneficial effects on oxidative stress, inflammation, and delayed onset muscle soreness following exercise. Furthermore, dietary supplements such as creatine, omega-3 fatty acids, and probiotics were associated with improved recovery capacity, reduced exercise-induced muscle damage, enhanced immune support, and improved adaptation to repeated training stimuli. The evidence suggests that combining multiple nutritional strategies may provide synergistic benefits for both recovery processes and athletic performance.

Conclusions:
Evidence-based nutritional strategies may effectively support exercise recovery, training adaptation, and sports performance in athletes and physically active individuals. Integrated approaches combining appropriate macronutrient intake, functional foods, and targeted supplementation appear to provide the greatest benefits for optimizing recovery and maintaining exercise performance. Further research is needed to determine optimal intervention protocols, long-term effects, and individualized approaches across different sports disciplines and athletic populations.

Keywords:
exercise recovery, athletic performance, training adaptation, sports performance, exercise physiology, muscle recovery, exercise-induced muscle damage, sports nutrition, ergogenic aids, nutritional interventions, creatine supplementation, probiotics, omega-3 fatty acids

Introduction

Optimizing exercise recovery is a fundamental component of athletic performance, training adaptation, and long-term athlete development. Effective recovery strategies enable athletes to maintain training intensity, reduce fatigue accumulation, minimize injury risk, and improve subsequent exercise performance [5,6].

Exercise-induced fatigue and muscle damage result from a combination of mechanical stress, metabolic disturbances, and inflammatory processes. High-intensity and prolonged physical activity can lead to depletion of glycogen stores, disruption of muscle fibers, and increased production of reactive oxygen species, all of which impair subsequent performance if recovery is inadequate [29,30]. Therefore, targeted nutritional interventions are essential to support regeneration and optimize adaptation to training stimuli.

Macronutrient intake is one of the most critical determinants of recovery. Protein consumption supports muscle repair and promotes muscle protein synthesis, which is essential for recovery and adaptation following resistance and endurance training [7,9]. Meta-analytical evidence confirms that protein supplementation enhances lean body mass and facilitates recovery processes, particularly when combined with structured training programs [9,10]. Additionally, the timing and distribution of protein intake throughout the day may further influence recovery outcomes and anabolic responses [11,16].

Carbohydrates play a crucial role in restoring muscle glycogen stores, which are a primary energy source during exercise. Rapid glycogen resynthesis is especially important for athletes engaged in multiple training sessions or competitions within a short time frame [8,13]. Research indicates that both the quantity and timing of carbohydrate intake significantly affect glycogen replenishment rates, thereby influencing recovery efficiency and subsequent performance [14,15].

Beyond macronutrients, there is growing interest in functional foods and bioactive compounds that may enhance recovery through anti-inflammatory and antioxidant mechanisms. Polyphenol-rich foods, such as tart cherry juice and berries, have been shown to reduce muscle soreness, oxidative stress, and inflammation following exercise [17–20]. These effects are thought to be mediated by their ability to modulate oxidative pathways and attenuate exercise-induced cellular damage [21].

Similarly, omega-3 fatty acids have demonstrated potential benefits in reducing delayed onset muscle soreness (DOMS) and inflammatory responses after exercise. Supplementation with eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) may support muscle recovery by influencing membrane stability and inflammatory signaling pathways [22–24]. Emerging evidence also highlights the role of gut microbiota in athletic performance and recovery, suggesting that probiotics may contribute to improved immune function, reduced gastrointestinal stress, and enhanced recovery capacity [25,26].

In addition to functional foods, several dietary supplements have been widely investigated for their role in recovery. Creatine supplementation, traditionally associated with improvements in strength and power, has also been shown to support recovery by reducing muscle damage and enhancing energy resynthesis [27,28]. These multifaceted effects make creatine one of the most extensively studied and effective ergogenic aids in sports nutrition.

Recent literature, including studies published in *Quality in Sport*, emphasizes the integrative role of diet and supplementation in optimizing recovery and performance. These studies highlight the importance of combining macronutrient strategies with targeted supplementation and functional foods to achieve optimal recovery outcomes [1–4].

Given the increasing complexity and volume of research in this field, there is a need for a comprehensive synthesis of current evidence. Therefore, this literature-based review aims to evaluate nutritional strategies supporting exercise recovery and athletic performance, with particular emphasis on functional foods and dietary supplementation in athletic populations.

Aim of the Study

The primary objective of this literature-based review is to evaluate nutritional strategies supporting exercise recovery and athletic performance, with particular emphasis on the role of functional foods and dietary supplementation in physically active individuals and athletes.

The secondary aims include:

1. To analyze the physiological mechanisms underlying post-exercise recovery, including muscle protein synthesis, glycogen resynthesis, inflammation, and oxidative stress, with particular emphasis on nutritional modulation of these processes [5,29].
2. To evaluate the effectiveness of macronutrient-based strategies, specifically protein and carbohydrate intake, in promoting muscle repair, adaptation, and restoration of energy stores following exercise [7–9,13–15].
3. To assess the impact of selected functional foods rich in bioactive compounds (e.g., polyphenols) on exercise-induced muscle damage, inflammation, and recovery outcomes [17–21].
4. To examine the role of dietary supplements, including omega-3 fatty acids, probiotics, and creatine, in modulating recovery processes and improving subsequent physical performance [22–28].

5. To compare the relative effectiveness of different nutritional strategies and identify practical applications for athletes across various types of physical activity.

Materials and Methods

I. Study Design and Scope

This study is a narrative literature-based review aimed at synthesizing current evidence regarding nutritional strategies that support post-exercise recovery in athletes. The methodology follows a structured narrative review approach based on a systematic search of the literature, focusing on transparency, reproducibility, and the inclusion of high-quality scientific evidence [6].

II. Literature Search Strategy

A structured literature search was conducted using major scientific databases, including PubMed, Scopus, and Google Scholar. The search included studies published up to 2025 and was limited to full-text articles available in English.

The following keywords and combinations were used: exercise recovery, sports nutrition, functional foods, dietary supplements, muscle damage, protein supplementation, glycogen resynthesis, omega-3 fatty acids, polyphenols, probiotics, creatine. Boolean operators (AND, OR) were applied to refine the search strategy. Additionally, reference lists of relevant articles were screened to identify further eligible studies.

III. Study Selection Criteria (PICOS Framework)

The selection of studies was based on the PICOS framework to ensure methodological consistency and relevance.

P (Population):

Human participants, including athletes, physically active individuals, and trained populations.

I (Intervention):

Nutritional interventions including:

functional foods (e.g., polyphenol-rich products)

dietary supplements (e.g., protein, creatine, omega-3, probiotics)

C (Comparison):

Placebo, control group, or standard diet.

O (Outcomes):

Primary outcomes:

markers of muscle recovery (e.g., muscle soreness, creatine kinase)

glycogen resynthesis

inflammatory and oxidative stress markers

performance recovery (e.g., time to exhaustion, strength restoration)

S (Study Design):

systematic reviews

meta-analyses

randomized controlled trials (RCTs)

high-quality narrative reviews

IV. Inclusion and Exclusion Criteria

Inclusion criteria:

- studies involving human participants
- studies examining nutritional interventions related to recovery
- peer-reviewed articles
- publications in English
- studies reporting measurable recovery-related outcomes

Exclusion criteria:

- animal studies

- non-peer-reviewed publications
- conference abstracts without full text
- studies not directly related to recovery processes

V. Data Extraction and Synthesis

Data were extracted from the selected studies and categorized into the following domains:

1. Macronutrient strategies
2. (protein and carbohydrate intake and timing) [7–9,13–15]
3. Functional foods
4. (polyphenols, antioxidant-rich products) [17–21]
5. Dietary supplements
6. (omega-3 fatty acids, probiotics, creatine) [22–28]
7. Physiological mechanisms of recovery
8. (inflammation, oxidative stress, muscle damage) [29,30]

For each study, the following information was collected:

- study design
- population characteristics
- intervention type and duration
- key outcomes

The synthesis of the literature was performed qualitatively, with emphasis on identifying consistent findings, discrepancies, and practical implications for athletes.

Results

I. Macronutrient Strategies in Post-Exercise Recovery

A. Protein Intake and Muscle Protein Synthesis

Protein intake plays a central role in post-exercise recovery by stimulating muscle protein synthesis (MPS) and promoting repair of exercise-induced muscle damage. Evidence from meta-analyses demonstrates that protein supplementation significantly enhances gains in lean body mass and improves recovery, particularly when combined with resistance training [9,10]. The effectiveness of protein intake depends not only on total daily intake but also on distribution and timing. Frequent ingestion of moderate protein doses throughout the day appears to optimize MPS and recovery processes [11,16]. Additionally, protein consumption immediately after exercise has been shown to accelerate recovery and support adaptive responses [7].

Beyond structural repair, protein intake may also reduce markers of muscle damage and perceived soreness, thereby facilitating faster return to performance [12]. These findings highlight protein as a foundational component of nutritional recovery strategies across various sports disciplines. Improved recovery may contribute to enhanced resistance training adaptations and subsequent athletic performance [9,10].

B. Carbohydrate Intake and Glycogen Resynthesis

Carbohydrates are essential for replenishing muscle glycogen stores depleted during exercise. Glycogen resynthesis is a key determinant of recovery, particularly in athletes performing repeated bouts of high-intensity or endurance exercise [8,13].

Studies indicate that rapid post-exercise carbohydrate intake significantly enhances glycogen restoration, especially when consumed within the early recovery window [14]. The rate of glycogen resynthesis is influenced by both the quantity and type of carbohydrates ingested, as well as the presence of co-ingested nutrients such as protein [15].

Furthermore, carbohydrate availability plays a crucial role in maintaining performance capacity during subsequent exercise sessions. Inadequate glycogen restoration has been associated with reduced endurance, increased fatigue, and impaired recovery [8]. Therefore, carbohydrate intake remains a critical element of effective recovery strategies. Adequate glycogen restoration

is essential for maintaining exercise capacity and performance during repeated training sessions.

II. Nutritional Interventions Supporting Recovery and Performance

A. Polyphenol-Rich Foods

Functional foods rich in polyphenols have gained increasing attention due to their potential to enhance recovery through antioxidant and anti-inflammatory effects. Tart cherry juice is one of the most extensively studied interventions, demonstrating significant reductions in muscle soreness, inflammation, and strength loss following exercise [17,20].

Similarly, consumption of berries and other polyphenol-rich foods has been associated with improved recovery of muscle function and reduced oxidative stress [19]. These effects are likely mediated by the ability of polyphenols to neutralize reactive oxygen species and modulate inflammatory pathways [21].

The consistent findings across multiple studies suggest that polyphenol-rich functional foods can effectively support recovery, particularly in endurance and high-intensity exercise contexts.

III. Omega-3 Fatty Acids and Inflammation Modulation

Omega-3 fatty acids, particularly EPA and DHA, have been shown to play a significant role in reducing exercise-induced inflammation and muscle soreness. Supplementation has been associated with decreased delayed onset muscle soreness (DOMS) and improved recovery outcomes following strenuous exercise [22].

Research indicates that omega-3 fatty acids may influence cell membrane integrity and inflammatory signaling, thereby reducing muscle damage and enhancing recovery processes [23]. Additionally, some studies report improved functional recovery and reduced markers of inflammation in athletes supplementing with omega-3 [24].

These effects may positively influence performance recovery in athletes exposed to high training loads.

IV. Gut Microbiota and Probiotics

Emerging evidence highlights the importance of gut microbiota in athletic performance and recovery. Probiotic supplementation has been shown to improve immune function, reduce gastrointestinal symptoms, and potentially enhance recovery capacity in athletes [25,26].

The modulation of gut microbiota may influence systemic inflammation and nutrient absorption, both of which are critical for optimal recovery. Additionally, improved gut health may contribute to reduced illness risk, allowing for more consistent training and recovery cycles.

Although this field is still developing, current findings suggest that probiotics represent a promising area in sports nutrition, particularly in the context of recovery optimization.

V. Creatine Supplementation and Recovery

Creatine is widely recognized for its role in enhancing strength and power, but growing evidence also supports its benefits in post-exercise recovery. Supplementation has been associated with reduced muscle damage, improved energy resynthesis, and faster recovery between exercise bouts [27].

Creatine may exert these effects by enhancing phosphocreatine stores, thereby improving ATP resynthesis and reducing metabolic stress during and after exercise [28]. Additionally, some studies suggest that creatine may attenuate inflammatory responses and oxidative stress, further supporting recovery.

These multifaceted effects position creatine as one of the most effective and well-supported supplements for both performance and recovery. Enhanced recovery capacity may support repeated high-intensity exercise performance.

VI. Integrated Nutritional Strategies

The combined application of macronutrients, functional foods, and dietary supplements appears to provide the most effective approach to post-exercise recovery. Evidence suggests that

integrating protein and carbohydrate intake with targeted supplementation and functional foods can synergistically enhance recovery outcomes [5,6].
Recent studies, including those published in Quality in Sport, emphasize the importance of a holistic nutritional approach, combining dietary strategies with supplementation tailored to the specific demands of the athlete and sport [1–4].

Discussion

The present literature-based review synthesizes current evidence on nutritional strategies supporting post-exercise recovery, highlighting the complementary roles of macronutrients, functional foods, and dietary supplements. The findings confirm that recovery is a multifactorial process influenced by metabolic, structural, and inflammatory mechanisms, all of which can be modulated through targeted nutritional interventions [5,29].

Macronutrients as the Foundation of Recovery

A consistent finding across the literature is the central role of macronutrients—particularly protein and carbohydrates—in recovery processes. Protein intake is essential for stimulating muscle protein synthesis and facilitating repair of exercise-induced muscle damage [7,9]. Evidence from meta-analyses demonstrates that protein supplementation enhances recovery outcomes and promotes favorable adaptations in muscle mass and strength [9,10].
However, the literature also emphasizes that not only the quantity but also the timing and distribution of protein intake are critical. Regular ingestion of protein throughout the day appears to optimize anabolic responses and improve recovery efficiency [11,16]. These findings reinforce the importance of structured nutritional planning in athletic populations.
Similarly, carbohydrate intake remains indispensable for restoring muscle glycogen stores. Rapid glycogen resynthesis is particularly important in athletes exposed to high training frequency or multiple competitions [8,13]. The effectiveness of carbohydrate strategies depends on timing, composition, and co-ingestion with protein, which may further enhance glycogen replenishment [14,15]. Together, these findings confirm that macronutrient strategies form the cornerstone of effective recovery protocols.

Functional Foods and Bioactive Compounds

Beyond macronutrients, increasing attention has been given to functional foods rich in bioactive compounds, particularly polyphenols. The reviewed studies consistently demonstrate that polyphenol-rich foods, such as tart cherry juice and berries, can reduce muscle soreness, inflammation, and oxidative stress following exercise [17–20].
These effects are primarily attributed to antioxidant and anti-inflammatory properties, which may attenuate exercise-induced cellular damage and accelerate recovery processes [21]. Importantly, the magnitude of these benefits appears to depend on factors such as dosage, duration of supplementation, and type of exercise performed.
Despite promising results, some variability in outcomes has been observed across studies. This heterogeneity may be explained by differences in study design, population characteristics, and the specific polyphenol sources used. Therefore, while functional foods represent a valuable addition to recovery strategies, their effects should be interpreted within the broader context of overall nutritional intake.

Anti-Inflammatory Strategies: Omega-3 Fatty Acids

Omega-3 fatty acids have emerged as another important nutritional intervention due to their role in modulating inflammation. The evidence suggests that supplementation with EPA and DHA can reduce delayed onset muscle soreness and improve recovery markers following exercise [22].
Mechanistically, omega-3 fatty acids influence inflammatory pathways and may enhance membrane fluidity, contributing to improved muscle function and recovery [23,24]. However,

the extent of these benefits may vary depending on dosage, duration, and baseline dietary intake.

It is also important to consider that excessive suppression of inflammation could theoretically interfere with training adaptations. Therefore, the use of omega-3 supplementation should be carefully tailored to the athlete's training phase and goals.

Emerging Role of Gut Microbiota

An emerging area of interest is the role of gut microbiota in recovery and performance. Probiotic supplementation has been shown to support immune function, reduce gastrointestinal symptoms, and potentially enhance recovery capacity [25,26].

The interaction between gut microbiota and systemic inflammation suggests that modulation of the gut environment may indirectly influence recovery processes. While current evidence is promising, this field remains relatively underexplored, and further research is needed to establish clear guidelines for probiotic use in athletes.

Creatine: Beyond Performance Enhancement

Creatine is one of the most extensively studied supplements in sports nutrition and is well known for its ergogenic effects. The findings of this review indicate that creatine also plays a significant role in recovery by enhancing phosphocreatine resynthesis, reducing muscle damage, and supporting repeated high-intensity performance [27,28].

Additionally, creatine may contribute to reduced inflammatory responses and improved cellular hydration, further supporting recovery mechanisms. These multifaceted effects make creatine a valuable component of both performance and recovery strategies.

Integrated Approach to Recovery

One of the key conclusions from the reviewed literature is that no single nutritional intervention is sufficient to optimize recovery. Instead, the most effective strategies involve a combination of macronutrient intake, functional foods, and targeted supplementation [5,6].

Recent publications, including those in Quality in Sport, emphasize the importance of individualized and sport-specific nutritional approaches that integrate dietary strategies with supplementation tailored to training demands [1–4]. This holistic perspective reflects the complexity of recovery processes and the need for multifaceted interventions.

An important observation emerging from the reviewed literature is the close relationship between recovery optimization and athletic performance. Effective post-exercise recovery strategies may improve training consistency, reduce accumulated fatigue, and enhance adaptation to exercise stimuli. Consequently, nutritional interventions supporting recovery may indirectly contribute to improvements in endurance, strength, and overall sports performance [5,8,27].

Limitations and Future Directions

Despite the strong body of evidence, several limitations should be acknowledged. First, variability in study design, participant characteristics, and intervention protocols makes direct comparison between studies challenging. Second, many studies focus on short-term outcomes, limiting the understanding of long-term effects of nutritional interventions on recovery and performance.

Additionally, much of the available research has been conducted in male or mixed populations, highlighting the need for more studies involving female athletes and diverse populations. Future research should also focus on personalized nutrition approaches, taking into account genetic, metabolic, and environmental factors.

Conclusion

The present literature-based review demonstrates that post-exercise recovery is a complex, multifactorial process that can be effectively supported through evidence-based nutritional strategies. The findings consistently highlight the fundamental role of macronutrients—

particularly protein and carbohydrates—in promoting muscle repair, enhancing muscle protein synthesis, and restoring glycogen stores following exercise [7–9,13].
In addition to macronutrients, functional foods rich in bioactive compounds, especially polyphenols, have shown promising effects in reducing muscle soreness, oxidative stress, and inflammation. These properties make them valuable components of recovery-oriented dietary interventions, particularly in high-intensity and endurance sports [17–21].
Dietary supplements, including omega-3 fatty acids, probiotics, and creatine, further contribute to optimizing recovery processes. Omega-3 fatty acids support the modulation of inflammatory responses, probiotics may enhance immune function and gut health, and creatine has demonstrated benefits not only in performance but also in reducing muscle damage and improving recovery capacity [22–28].
Importantly, the evidence suggests that the most effective recovery strategies are those that integrate multiple nutritional approaches rather than relying on a single intervention. A combination of adequate macronutrient intake, functional foods, and targeted supplementation appears to provide synergistic benefits and optimize recovery outcomes [5,6].
Recent literature, including studies published in Quality in Sport, emphasizes the importance of individualized nutritional strategies tailored to the specific demands of the athlete, sport discipline, and training load [1–4]. Such an approach allows for more precise optimization of recovery and performance.
Despite the growing body of evidence, further research is needed to better understand long-term effects, optimal dosing strategies, and individual variability in response to nutritional interventions. Future studies should also focus on underrepresented populations and the role of personalized nutrition in athletic recovery.
The findings of this review indicate that evidence-based nutritional strategies play an important role in supporting exercise recovery, training adaptation, and athletic performance.

Disclosure

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All data analyzed in this study are included in the cited articles.

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The authors declare no conflict of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process
In preparing this work, the authors used ChatGPT (OpenAI) for the purpose of assisting with language refinement and structuring the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final content of the publication.

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