Review

From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition

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Review

From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition

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Abstract: Post-exercise recovery is fundamental to optimizing athletic performance, focusing on muscle repair, glycogen replenishment, rehydration, and reducing exercise-induced inflammation. This review examines the evolving landscape of recovery nutrition, highlighting the transition from conventional supplements—such as protein, carbohydrates, creatine, and branched-chain amino acids (BCAAs)—to functional foods rich in bioactive compounds. Emerging evidence supports the efficacy of functional foods like tart cherry juice, turmeric, and omega-3 fatty acids in mitigating oxidative stress and inflammation, thus accelerating recovery. Additionally, probiotics and prebiotic-rich foods are gaining recognition for enhancing gut health, promoting nutrient absorption, and strengthening immune function, which are crucial in recovery processes. The concept of personalized nutrition, guided by genetic and metabolic profiling, is explored as a promising approach to tailor recovery strategies to individual physiological needs. Continued research into the long-term effects of supplements, the role of functional foods, and nutrient interactions is essential for developing more comprehensive and individualized recovery protocols. Integrating functional foods with personalized nutrition offers a holistic strategy to enhance recovery, optimize performance, and promote long-term health in athletes.

Keywords: muscle protein synthesis; nutrient bioavailability; exercise-induced inflammation; metabolic profiling; athletic performance recovery

1. Introduction

1.1. Background and Importance of Post-Exercise Recovery

Post-exercise recovery is not merely a phase but a fundamental component of athletic performance, essential for optimizing outcomes, preventing injuries, and maintaining overall health [1]. During physical exertion, the body experiences muscle damage, energy depletion, and fluid loss, which must be addressed during recovery to restore physiological balance and prepare for subsequent exercise [2]. Critical elements of recovery include muscle tissue repair, glycogen restoration, rehydration, and the attenuation of inflammation. Nutrition plays a pivotal role in this process, with protein facilitating muscle regeneration, carbohydrates replenishing glycogen stores, and adequate hydration ensuring the replacement of fluids and electrolytes [3,4]. A well-managed recovery enhances physical readiness and contributes to mental well-being by alleviating stress and mitigating the risk of overtraining, ultimately enabling individuals to maximize the benefits of their training and sustain long-term health [5,6].

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1.1.1. The Crucial Role of Nutrition in Post-Exercise Recovery

Post-exercise recovery is essential for optimizing athletic performance and maintaining physical well-being. This phase supports tissue repair, replenishes energy stores, and prepares the body for subsequent physical activity. Adequate nutrition during recovery is vital for enhancing muscle repair, reducing the risk of injury, and preventing overtraining [1,3,7]. The microtears that occur in muscle fibers during exercise, which are necessary for muscle growth, require sufficient post-exercise protein intake to supply the amino acids necessary for repair and regeneration [8,9]. Additionally, restoring glycogen, which is depleted during intense physical activity, is critical for ensuring that muscles are adequately prepared for future training [10].

Antioxidants, including vitamins C and E, are integral to mitigating oxidative stress, while minerals such as calcium, magnesium, and potassium are essential for maintaining muscle function and electrolyte balance [11]. Proper hydration and electrolyte replenishment are critical to preventing dehydration and sustaining optimal muscle performance [12].

Effective recovery relies on strategic nutrient timing. Personalized nutrition plans enhance recovery by customizing nutrient intake to individual needs, improving performance, and reducing injury risk.

1.1.2. Overview of Current Trends and Practices in Recovery Nutrition

Recovery nutrition has undergone substantial advancements, incorporating diverse strategies and practices to enhance the recovery process for athletes. This review outlines contemporary trends and widely accepted methodologies in the field. A key component of recovery nutrition is the timing of nutrient intake. Consuming proteins and carbohydrates during the "anabolic window," which spans 30 minutes to two hours post-exercise, is critical for optimizing muscle protein synthesis and glycogen replenishment [13,14]. This practice, known as nutrient timing, is widely recommended for athletes aiming to achieve optimal recovery. Additionally, the type and quality of protein consumed are vital in ensuring effective recovery. Due to its high biological value and rapid absorption, whey protein remains a preferred choice, while plant-based proteins are gaining attention for their sustainability and associated health benefits [15]. Furthermore, Branched-Chain Amino Acids (BCAAs) and essential amino acids are frequently emphasized for their contributions to muscle repair, soreness reduction, and overall recovery enhancement [16].

Post-exercise carbohydrate intake is essential for replenishing depleted muscle glycogen stores, with high-glycemic-index carbohydrates recommended immediately after exercise to expedite glycogen restoration [17]. Combining carbohydrates with proteins can further augment glycogen storage and muscle repair, improving recovery outcomes [18]. Adequate rehydration is also critical to recovery, as it replaces fluids lost through sweat. Sports drinks containing electrolytes such as sodium, potassium, and magnesium help maintain fluid balance and prevent dehydration, which is necessary for proper muscle function and cramp prevention [12].

Moreover, functional foods with anti-inflammatory properties, including tart cherry juice, turmeric, and omega-3 fatty acids, have been shown to reduce exercise-induced inflammation and alleviate muscle soreness [19,20]. Gut health has also emerged as a crucial aspect of recovery, with probiotics and prebiotic-rich foods incorporated into recovery diets to support gut microbiota and enhance nutrient absorption [21]. Additionally, supplements such as creatine, beta-alanine, and caffeine are frequently utilized for their performance-enhancing and recovery-boosting effects [22]. Ensuring adequate intake of vitamins and minerals, especially those critical for energy production and muscle function, is paramount to optimizing recovery.

Technological advancements, such as mobile applications, now enable personalized nutrition plans, track dietary intake, and provide reminders for nutrient timing, thereby improving adherence to recovery protocols [23]. Further, genetic testing and metabolic profiling innovations facilitate highly individualized nutrition strategies, allowing recovery interventions to be precisely tailored to the athlete's unique physiological profile, maximizing the efficacy of these interventions [24].

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1.2. Objective of the Review

This review explores the emerging role of food supplements and functional foods in enhancing post-exercise recovery. It highlights the effectiveness of protein supplements, especially those with essential amino acids and BCAAs, in supporting muscle repair while emphasizing the benefits of combining carbohydrates and proteins for glycogen replenishment. Functional foods like tart cherry juice, turmeric, and omega-3 fatty acids are recognized for their anti-inflammatory effects. The review also addresses the importance of gut health, focusing on probiotics and prebiotics for improved nutrient absorption and immune function. Future directions include personalized nutrition based on genetic profiling to optimize recovery strategies for athletes.

2. Overview of Post-Exercise Recovery

2.1. Physiological Aspects of Recovery

Muscle repair and hypertrophy are fundamental components of post-exercise recovery, particularly for athletes seeking to improve performance and mitigate the risk of injury. Exercise, especially resistance training or high-intensity activities, induces microtears in muscle fibers [3]. Although this damage might seem detrimental, it is essential for muscle adaptation and strengthening. The muscle repair process involves a series of complex physiological mechanisms to reconstruct damaged fibers, thus enhancing their resilience to future stressors. Muscle regeneration occurs in two distinct stages: degeneration of the damaged fibers and a regenerative phase. Myogenic cells proliferate, differentiate, and fuse during the regenerative phase to repair or form new muscle fibers. Degeneration begins with necrosis of the damaged fibers, often resulting from disruptions to the sarcolemma and increased permeability of the myofibers. This is followed by activating inflammatory and myogenic cells, critical in facilitating muscle repair [25]. Central to this repair is muscle protein synthesis (MPS), a biological process in which cells produce new proteins to replace those damaged during exercise [26]. Adequate post-exercise protein intake provides the amino acids required for this process. Essential amino acids (EAAs), particularly Branched-Chain Amino Acids (BCAAs) like leucine, isoleucine, and valine, play a key role in stimulating MPS [27]. Leucine, in particular, activates the mTOR pathway, a major regulator of cell growth and muscle protein synthesis. Whey protein, with its high biological value and rapid absorption, is widely regarded as one of the most effective supplements for post-exercise recovery, providing a rich source of EAAs and BCAAs to expedite muscle repair [28].

Carbohydrates are also crucial for replenishing glycogen stores depleted during exercise, restoring energy levels, and supporting muscle recovery. Glycogen, stored in skeletal muscle and the liver, is the primary energy substrate during high-intensity exercise, making its restoration essential for effective recovery and optimal subsequent performance [3]. The timely consumption of carbohydrates, especially those with a high glycemic index (GI), within the "anabolic window" (30 minutes to two hours post-exercise) is considered the most effective method for rapid glycogen replenishment [14]. Additionally, the simultaneous consumption of carbohydrates and protein post-exercise enhances muscle repair by promoting insulin release, facilitating amino acid uptake into muscle cells, thus promoting MPS. Studies have shown that ingesting a small amount of protein (0.2–0.4 g/kg/hr) combined with carbohydrates (0.8 g/kg/hr) stimulates insulin release and achieves glycogen repletion rates comparable to those achieved by consuming 1.2 g/kg/hr of carbohydrates alone. The co-ingestion of carbohydrates and protein during the early stages of recovery has been shown to positively affect subsequent exercise performance, especially for athletes engaged in multiple training or competition sessions within a short time frame [29]. Glycogen replenishment strategies should be tailored to the individual, accounting for the specific type and intensity of exercise, while a carbohydrate-rich diet supports sustained energy availability and recovery [10,29].

Maintaining fluid and electrolyte balance is another critical aspect of post-exercise recovery, necessary for optimal physiological function and preventing performance declines associated with dehydration [30,31]. Significant losses of fluids and electrolytes, including sodium, potassium,

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magnesium, and calcium, occur through sweat during exercise and, if not adequately replaced, can impair muscle function [32]. Hydration is essential for maintaining blood volume, regulating body temperature, and ensuring proper muscle function [33]. Sports drinks containing electrolytes are recommended for prolonged or high-intensity exercise, while electrolyte-rich foods can also help replenish minerals lost during exercise [34].

2.2. Nutritional Needs for Effective Recovery

Macronutrients—proteins, carbohydrates, and fats—are fundamental elements of an athlete's diet, serving critical roles in energy production, muscle repair, and overall health. A comprehensive understanding of the specific functions of each macronutrient can enable athletes to optimize their nutrition for enhanced performance and recovery.

Proteins are particularly important for muscle repair and growth, supplying amino acids necessary for synthesizing new muscle tissue. This process is crucial following intense physical activity, which induces muscle damage. Resistance exercise stimulates muscle protein synthesis (MPS) and hypertrophy, while endurance exercise triggers adaptations in mitochondrial content and oxidative capacity. Exercise increases mRNA expression, facilitating protein synthesis and leading to adaptive changes in muscle protein content [35]. Proteins also play a vital role in immune system function, helping the body recover from injury and combat illness. Damage-associated molecular patterns (DAMPs), such as High-mobility group box 1 protein (HMGB1), are released by necrotic cells and activate immune responses. When oxidized, HMGB1 binds to various receptors, mediating signaling pathways that promote inflammation and tissue repair [36]. Additionally, proteins form the basis of many enzymes and hormones, essential for metabolic processes and maintaining physiological function [37]. High-quality protein sources include lean meats, fish, eggs, dairy products, legumes, nuts, and seeds. A balanced intake of animal and plant-based proteins is recommended to ensure athletes' complete amino acid profile.

Carbohydrates are the body's primary energy source, particularly during high-intensity physical activity. Stored as glycogen in muscles and the liver, carbohydrates are readily mobilized to meet energy demands during exercise. Studies have demonstrated that varying muscle glycogen levels, achieved through carbohydrate manipulation, significantly influence exercise performance. Higher glycogen concentrations are associated with improved performance and reduced perceived exertion during intense exercise [38]. Post-exercise carbohydrate intake is essential for replenishing glycogen stores, aiding in energy restoration, and preparing muscles for subsequent training sessions. Research indicates that carbohydrate consumption is the primary factor influencing muscle glycogen resynthesis and repeated exercise capacity, with protein supplementation enhancing these effects when carbohydrate intake is insufficient [10]. Carbohydrates also play a key role in brain function, providing glucose as the primary fuel for cognitive processes. Glucose metabolism in the brain involves several pathways, including glycolysis, the pentose phosphate pathway, and glycogen turnover, all essential for ATP production and biosynthesis [39]. Athletes should prioritize complex carbohydrate sources such as whole grains, fruits, vegetables, and legumes, which provide sustained energy release alongside essential vitamins and minerals.

Fats are equally important in supporting post-exercise recovery, as they provide a long-term energy reserve and contribute to numerous physiological processes. They are essential for the structural integrity of cell membranes and hormone production, particularly those involved in metabolism and reproductive health. Fats also facilitate the absorption of fat-soluble vitamins (A, D, E, and K), critical for various bodily functions [30,31]. Healthy fat sources, such as avocados, nuts, seeds, olive oil, and fatty fish like salmon, supply essential fatty acids, including omega-3 and omega-6, which possess anti-inflammatory properties and support cardiovascular health [32]. Incorporating these fats into post-exercise nutrition can reduce inflammation, promote recovery, and enhance overall health. Striking the appropriate balance of fat, protein, and carbohydrate intake based on individual needs and exercise demands is essential for optimizing recovery and long-term athletic performance [33,34].

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Balancing macronutrient intake according to an athlete's specific physiological requirements, training goals, and the demands of their sport is key to maximizing performance outcomes. Prioritizing minimally processed, nutrient-dense foods ensures the intake of essential micronutrients and bioactive compounds that support both recovery and long-term health.

Micronutrients, including vitamins and minerals, play critical roles in numerous physiological processes, including energy production, immune function, bone health, and muscle tissue repair [35]. Although required in smaller amounts than macronutrients, they are vital for optimizing athletic performance and overall health. Vitamins, for instance, are involved in various essential functions. Vitamin A contributes to vision, immune function, skin health, bone growth, and the maintenance of epithelial tissues [36]. B vitamins (B1, B2, B3, B6, B12, folate, biotin, and pantothenic acid) are central to energy production, as they help convert dietary energy into ATP while supporting red blood cell formation and maintaining nervous system health [37]. Vitamin C is crucial for collagen synthesis, repairing tissues such as tendons and ligaments, and functions as an antioxidant, protecting cells from free radical damage [38]. Vitamin D is essential for calcium absorption and bone health while supporting immune function and muscle strength [39]. Vitamin E is an antioxidant that protects cell membranes from oxidative stress and contributes to immune function [40]. Vitamin K is critical for blood clotting and bone metabolism [41].

Micronutrients also enhance post-exercise recovery by supporting the physiological processes necessary for repair and adaptation. Minerals such as calcium and magnesium are indispensable for muscle function, bone health, and electrolyte balance, all vital for recovery from physical exertion [42]. Iron in lean meats and whole grains is necessary for energy metabolism and red blood cell production, restoring energy levels [43]. Ensuring adequate intake of these micronutrients promotes efficient recovery, helping to minimize fatigue and support long-term performance improvements.

3. Role of Food Supplements in Post-Exercise Recovery

Food supplements are critical in enhancing post-exercise recovery by delivering key nutrients necessary for muscle repair, energy restoration, and overall physiological functioning. This section examines the various categories of food supplements frequently employed in post-exercise recovery, assessing their effectiveness, benefits, and potential limitations.

3.1. Types of Food Supplements

3.1.1. Protein Supplements (Whey, Casein, Plant-Based)

Whey Protein: Whey protein is widely recognized for its rapid digestion and absorption, making it an optimal choice for post-exercise recovery. Its fast absorption allows for the swift delivery of amino acids to muscle tissues, which is particularly important during the anabolic window. Whey protein is rich in essential amino acids (EAAs), especially leucine, which is crucial in stimulating muscle protein synthesis by activating the mTOR pathway, a key regulator of cellular growth and protein synthesis essential for muscle repair and hypertrophy [44]. Furthermore, whey protein is highly versatile and can easily be incorporated into shakes, smoothies, and other recipes, providing a convenient means of boosting protein intake. It is available in various forms—concentrates, isolates, and hydrolysate—each differing in protein content and absorption rates [45].

Casein Protein: Casein, a slow-digesting protein found in dairy products, differs from whey in that it forms a gel-like substance in the stomach, resulting in a sustained release of amino acids into the bloodstream. This slow release makes casein particularly effective for prolonged muscle repair and growth, making it a suitable option for nighttime consumption to support overnight muscle recovery [46]. As the body is fasting during sleep, casein supplies a steady stream of amino acids, preventing muscle breakdown and promoting tissue repair [47]. Casein is also a valuable source of calcium, a mineral essential for bone health and proper muscle function [48].

Plant-Based Proteins: Plant-based protein supplements, derived from sources such as peas, soy, and hemp, offer a viable alternative to dairy proteins for individuals with lactose intolerance, dairy allergies, or those following vegan diets. Historically, plant-based proteins were considered inferior

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due to their incomplete amino acid profiles. However, advancements in food science have led to formulations that provide a complete spectrum of EAAs essential for muscle repair and overall health [49]. Despite these improvements, plant-based proteins still face challenges in matching the efficacy of animal proteins in enhancing athletic performance. A Bayesian meta-analysis revealed that while plant-based proteins are more effective than consuming low or no protein, they are generally less effective than animal-based proteins, such as whey or milk, in promoting muscle strength and endurance [50]. Furthermore, some plant proteins, particularly those from legumes such as soy and peas, may pose allergenic risks for certain individuals, requiring innovative methods to reduce their allergenicity [51,52]. These methods include chemical, biochemical, and non-thermal physical treatments designed to make plant proteins safer for consumption by sensitive populations [51]. The development of plant-based alternatives extends beyond protein supplements to include dairy analogs, such as fermented cheeses made from cashews, soy, and other plant sources, which mimic the characteristics of traditional dairy products through fermentation with specific cultures [53]. This innovation addresses dietary preferences and environmental concerns related to animal protein production, positioning plant proteins as sustainable, nutritious, and functional ingredients in modern diets [49]. While plant-based proteins have considerably improved nutritional adequacy and application, further research is necessary to overcome sensory and functional limitations and improve consumer acceptance.

In summary, protein supplements are fundamental to post-exercise recovery, with each type offering distinct advantages. Research shows that while plant-based protein supplements outperform low- or no-protein intake in enhancing athletic performance, they are generally less effective than animal-based proteins such as whey or milk in improving muscle strength and endurance [50]. However, plant proteins have been linked to a reduced incidence of metabolic syndrome, underscoring their potential health benefits beyond muscle recovery [54].

3.1.2. Branched-Chain Amino Acids (BCAAs)

Branched-chain amino acids (BCAAs), comprising leucine, isoleucine, and valine, are essential amino acids that play a pivotal role in promoting muscle protein synthesis (MPS) and mitigating muscle protein breakdown (MPB), thus facilitating a net anabolic response in skeletal muscle [55]. These amino acids are essential for athletes and physically active individuals, as they enhance energy production during exercise while supporting overall muscle health. BCAAs influence the mechanistic target of rapamycin (mTOR) signaling pathway, a critical regulator of translation initiation in human muscle, which significantly impacts MPS, particularly in the post-exercise period [55]. However, despite their widespread use, the evidence regarding the efficacy of BCAA supplementation in promoting muscle hypertrophy, strength gains, and reducing post-exercise muscle soreness in resistance training remains inconclusive. Nonetheless, BCAAs may have therapeutic potential in specific medical conditions such as liver cirrhosis [56]. Additionally, research has shown that BCAAs enhance macrophage polarization, a crucial aspect of repairing exercise-induced muscle damage (EIMD), by promoting the proliferation and differentiation of muscle satellite cells through pathways such as mTORC1-HIF1α-glycolysis, underscoring their role in inflammation and muscle repair [57]. While BCAAs are integral to muscle health and energy production, their efficacy may be influenced by various factors, necessitating a personalized approach in their use for sports nutrition and therapeutic applications.

Leucine, a key component of BCAAs, is particularly effective at stimulating muscle protein synthesis by activating the mTOR pathway, essential for post-exercise muscle repair and growth. This corresponds with evidence suggesting that BCAA supplementation can reduce muscle soreness and fatigue, thereby lowering the risk of injuries, such as ankle sprains, in sports like basketball by promoting muscle stability and reducing soreness markers and creatine kinase levels in the blood [58]. Furthermore, BCAAs contribute to the reduction of muscle protein breakdown by decreasing the activity of proteolytic enzymes, thus preserving muscle tissue during prolonged exercise. This preservation is crucial, as BCAAs can serve as an additional energy source when glycogen stores are depleted, enhancing endurance and supporting sustained athletic performance [59]. Additionally,

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BCAAs have been shown to positively influence lipid and glucose metabolism, which aids in efficient energy management during physical activity [60]. Moreover, BCAAs reduce mental and physical fatigue by competing with tryptophan, consequently lowering serotonin levels and enabling athletes to maintain higher performance levels [61]. However, excessive intake of BCAAs may lead to adverse effects, such as contributing to the progression of atherosclerosis by inducing inflammation in macrophages, underscoring the importance of moderation and proper metabolic management in their consumption [62]. Overall, BCAAs offer a multifaceted approach to enhancing athletic performance, from stimulating muscle synthesis and providing energy to reducing fatigue. Still, they must be consumed carefully, considering their broader metabolic effects.

3.1.3. Creatine

Creatine monohydrate is one of the most extensively studied supplements, recognized for its significant role in enhancing post-exercise recovery and supporting athletic performance. Its primary function involves increasing phosphocreatine reserves within muscle tissue, facilitating the rapid regeneration of adenosine triphosphate (ATP), the primary energy source for high-intensity physical activities. This enhancement in ATP production is critical for recovery, as it enables quicker replenishment of energy stores following intense exercise, thereby reducing fatigue and allowing athletes to return to optimal performance more rapidly [63]. Creatine supplementation has also supported recovery by minimizing muscle damage and inflammation following exhaustive physical activity, leading to faster muscle repair. This is accomplished through creatine's anti-inflammatory effects in skeletal muscle and the brain, which aid in reducing fatigue and maintaining higher levels of spontaneous activity post-exercise [64].

Furthermore, creatine helps delay the onset of muscle fatigue, enabling longer and more intense training sessions, indirectly contributing to improved muscle recovery [65]. By promoting increased water retention within muscle cells and enhancing muscle protein synthesis, creatine creates an optimal environment for muscle repair and growth, further aiding recovery [63]. Additionally, incorporating creatine into post-exercise recovery protocols accelerates physical repair processes and may benefit cognitive recovery. This is due to creatine's role in supporting ATP production in the brain, which may enhance mental clarity and cognitive endurance, though further research is required to substantiate these effects [66,67].

In summary, creatine is a highly effective supplement for athletes seeking to improve physical and cognitive recovery, enabling sustained performance and long-term improvement in training outcomes.

3.1.4. Electrolyte Supplements

Electrolyte supplementation is essential for effective post-exercise recovery, as it aids in maintaining fluid balance, supporting nerve function, and ensuring proper muscle contractions. During exercise, particularly in hot or humid conditions, substantial amounts of electrolytes, such as sodium, potassium, magnesium, and calcium, are lost through sweat. Consequently, replenishing these electrolytes is necessary to restore physiological balance and prevent dehydration [68,69]. Sodium and chloride play critical roles in maintaining extracellular fluid balance. At the same time, potassium and magnesium are key for regulating intracellular fluid levels and are vital for optimal muscle and nerve function [68]. Additionally, calcium and magnesium are essential for muscle contraction and relaxation, helping to prevent cramps and promote efficient muscle recovery [69,70]. Maintaining adequate electrolyte levels post-exercise supports nerve transmission, muscle coordination, and overall recovery, thereby reducing muscle soreness and fatigue while facilitating faster recovery [71]. Proper electrolyte replenishment can also help delay the onset of fatigue, enabling athletes to sustain performance during subsequent training sessions [3]. Common methods for electrolyte replenishment include sports drinks, electrolyte tablets, and powders, all of which help prevent post-exercise dehydration and prepare the body for future exertion [68]. Athletes with high sweat rates or those training in challenging environmental conditions may benefit significantly from

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incorporating electrolytes into their recovery protocols, ensuring sustained performance and effective recovery [69].

In addition, natural fruit-derived antioxidants, rich in polyphenols, can complement electrolyte supplementation by protecting muscle cells from oxidative damage caused by reactive oxygen species, further enhancing recovery and athletic performance [71]. However, despite the established benefits of electrolyte replenishment, knowledge regarding electrolyte, mineral, and vitamin alterations post-exercise, particularly following traumatic brain injury, remains limited. Further research is necessary to optimize recovery strategies in these contexts [72].

3.2. Benefits and Potential Drawbacks of Food Supplements

Food supplements play a pivotal role in addressing the nutritional needs of athletes, who often experience increased energy and nutrient demands due to their rigorous training regimens. These supplements offer numerous advantages, such as enhancing muscle repair and recovery, by providing essential amino acids through products like protein powders and Branched-Chain Amino Acids (BCAAs) [73]. BCAAs, creatine, and anti-inflammatory nutrients like omega-3 fatty acids reduce muscle soreness and inflammation, promoting quicker recovery [74]. Electrolyte supplementation is vital for maintaining fluid balance and preventing dehydration during intense or prolonged physical activity, which is critical for sustaining athletic performance and health [75]. Additionally, multivitamins and minerals often address potential nutrient deficiencies, ensuring athletes receive all the essential vitamins and minerals necessary for optimal performance and health [76]. The convenience offered by food supplements is particularly beneficial for athletes with demanding schedules, as they provide an efficient means of meeting nutritional requirements without the need for extensive meal preparation [77]. Although a "food first" approach is recommended, supplements can be a practical option when dietary intake alone is insufficient to meet the nutritional demands of an athlete's lifestyle [76]. Moreover, the use of nutritional supplements is supported by the need to enhance athletes' adaptive responses, leading to improved performance and recovery [75]. The development of evidence-based functional foods that target muscle recovery, endurance, and strength is advancing sports nutrition innovation, underscoring the role of supplements in contemporary athletic practices [77]. While supplements should not replace a balanced diet, they remain valuable in supporting athletes' nutritional needs and performance objectives.

Despite the benefits of food supplements in addressing specific nutritional requirements, their use also presents potential drawbacks that warrant consideration. One primary concern is the over-reliance on supplements, which can detract from consuming a balanced diet rich in whole foods that provide a broader array of nutrients and bioactive compounds that supplements cannot fully replicate [78]. Gastrointestinal issues, such as bloating, gas, or cramps, may occur with certain supplements, particularly those containing protein powders, lactose, or artificial additives. Additionally, allergic reactions to ingredients like soy or whey protein may occur, requiring careful selection of alternative protein sources [79]. The supplement industry's regulatory landscape is less stringent than pharmaceuticals, raising concerns regarding product quality and purity. This can result in supplements containing contaminants, mislabeled, or lacking the stated amounts of active ingredients, highlighting the importance of choosing third-party tested and certified products for quality assurance [80]. Further, the presence of unauthorized pharmaceuticals in some food supplements, as reported by the Rapid Alert System for Food and Feed (RASFF) database, poses significant health risks, underscoring the need for a harmonized nutrivigilance system to improve safety and quality standards [81]. Excessive intake of certain supplements, particularly fat-soluble vitamins such as A, D, E, and K, may lead to nutrient imbalances and potential toxicity due to their accumulation in the body, emphasizing moderation and informed use [82]. Additionally, the expanding market for dietary supplements, driven by increased incidence of lifestyle diseases and the rise of personalized nutrition, calls for advancements in nutrient delivery systems to address challenges such as poor dispersibility and instability of bioactive compounds in food matrices [82].

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While supplements can be beneficial, they should be used judiciously and with a balanced diet to mitigate potential risks.

In conclusion, while food supplements can effectively support nutritional needs, enhance muscle repair, reduce soreness, improve hydration, and facilitate overall recovery, it is essential to use them strategically. Athletes should prioritize a balanced diet as the foundation of their nutritional strategy, using supplements to complement, rather than replace, whole foods. Additionally, attention to supplements' quality, purity, and appropriate usage can mitigate potential drawbacks, ensuring they positively contribute to an athlete's health and performance. Table 1 outlines the comprehensive role of food supplements in enhancing post-exercise recovery, focusing on their specific contributions to recovery mechanisms and overall athletic performance.

Table 1. Comprehensive Role of Food Supplements in Post-Exercise Recovery.

Supplement Name	Supplement Key Feature	Benefits of Post-Exercise Recovery	Cited References
Whey Protein	Rapid digestion and absorption; rich in essential amino acids (EAAs)	Accelerates muscle protein synthesis (MPS) and optimizes post-exercise recovery in the anabolic window.	Gu [9], Snijders et al. [8], Dreyer et al. [27], White [26], Bonilla et al. [3]
Casein Protein	Slow-digesting, prolonged amino acid release	It provides sustained amino acid delivery, supports overnight muscle repair, and reduces catabolism.	Abbott et al. [46], Dela Cruz & Kahan [47], Liu et al. [48], McGlory et al. [35], Chargé & Rudnicki [25]
Plant-Based Proteins	Non-dairy alternatives derived from soy, pea, hemp	It provides essential amino acids for muscle repair, is suitable for vegans, and supports nitrogen balance.	Zhang et al. [49], Zhao et al. [50], Lorinczova et al. [15], Howatson et al. [16], Marr [78]
Branched-Chain Amino Acids (BCAAs)	Contains leucine, isoleucine, and valine; influences mTOR signaling	Reduces muscle soreness and exercise-induced muscle damage (EIMD), stimulates mTOR pathway.	Kaspy et al. [55], Bieńkowski et al. [56], Lane et al. [28], Srinivasan [58], Fachada et al. [59]
Creatine	Enhances ATP resynthesis, boosts phosphocreatine stores	It enhances energy replenishment, supports high-intensity performance, and reduces fatigue.	Wax et al. [63], Yokota et al. [64], Forbes et al. [65], Sandkühler et al. [66], Forbes et al. [67]
Electrolytes	Replenishes sodium, potassium, magnesium, and calcium lost through sweat	Restores electrolyte balance, prevents dehydration, and reduces muscle cramps.	Peden et al. [68], Garrison et al. [69], Shirreffs & Sawka [12], Evans et al. [30], Trangmar & González-Alonso [32]

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4. Functional Foods and Their Impact on Recovery

Functional foods offer health benefits beyond essential nutritional value, often containing bioactive compounds or added ingredients that contribute to improved health and wellness. These foods can be crucial in enhancing recovery for athletes and physically active individuals by supporting vital physiological functions and promoting overall well-being.

4.1. Definition and Examples of Functional Foods

Functional foods are characterized as those that offer health benefits beyond their basic nutritional content, playing a pivotal role in enhancing various physiological functions essential for recovery and long-term well-being. These foods can either naturally contain beneficial compounds or be fortified with added ingredients to improve their health-promoting properties. For example, probiotics—live microorganisms found in foods such as yogurt, kefir, and fermented vegetables—support gut health and bolster immune function by inhibiting pathogenic bacteria and enhancing the intestinal barrier [83,84]. Similarly, prebiotics, which are present in foods like chicory root, garlic, onions, and bananas, serve as substrates for beneficial gut bacteria, promoting digestive health and enhancing the diversity of the gut microbiota, which is crucial for maintaining homeostasis and disease prevention [83,85]. Antioxidant-rich foods, including berries, dark chocolate, and green tea, reduce oxidative stress and inflammation, both of which are vital for recovery and overall health [86]. Additionally, anti-inflammatory foods such as turmeric, fatty fish, and nuts provide healthy fats and antioxidants that support recovery by mitigating inflammation and improving metabolic health [86]. Functional foods also encompass fortified products, such as calcium-fortified orange juice and vitamin D-fortified milk, which promote bone health, and omega-3-enriched eggs, which support cardiovascular health [85,87]. Incorporating these foods into the diet can significantly enhance recovery by improving gut health, reducing inflammation, offering antioxidant protection, and supporting bone and cardiovascular health. This comprehensive nutritional approach not only aids athletes in optimizing their performance but also contributes to overall health and vitality, as evidenced by extensive research on functional foods [87].

4.2. Functional Foods for Recovery

4.2.1. Dairy Products (e.g., Milk and Yogurt)

Dairy products, particularly milk, are recognized as effective functional foods that significantly aid in post-exercise recovery for athletes, owing to their comprehensive nutritional composition. Milk contains two primary proteins, whey and casein, which play critical roles in muscle repair and growth. Whey protein is rapidly absorbed, making it ideal for immediate post-exercise recovery, while casein provides a sustained release of amino acids, supporting prolonged muscle repair. These proteins supply all essential amino acids required for muscle protein synthesis, vital for promoting recovery and enhancing athletic performance [88]. Furthermore, milk is a rich source of calcium. It is often fortified with vitamin D, essential for maintaining bone density and skeletal health—critical for athletes engaging in strenuous physical activities [89]. Additionally, the electrolytes found in milk, such as potassium and sodium, help regulate fluid balance and promote rehydration, reducing the risk of dehydration following intense exercise. This is particularly important as dehydration can impair muscle performance, endurance, and strength [90].

Research has also demonstrated that milk consumption post-exercise can modulate inflammation, a key factor in recovery. Studies indicate that milk reduces the inflammatory response, as evidenced by lower concentrations of specific cytokines post-exercise than carbohydrate-based drinks [88]. Moreover, post-exercise milk consumption has been associated with reduced energy intake at subsequent meals, which may benefit athletes in managing energy balance and recovery [89]. While research on the effects of milk on intestinal health and exercise-induced inflammation suggests that milk-based beverages do not significantly mitigate exercise-related intestinal injury, they may improve work output during prolonged activities such as cycling [91]. The combination of

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proteins, vitamins, minerals, and electrolytes in milk underscores its value as a component of an athlete's post-exercise nutrition strategy.

Yogurt, particularly Greek yogurt, is another highly effective functional food for post-exercise recovery. Its high protein content supports muscle repair and recovery, making it especially suitable for athletes and physically active individuals [92]. The probiotics found in yogurt, such as Lactobacillus, contribute to gut health by balancing intestinal flora, enhancing nutrient absorption, and reducing inflammation—crucial for efficient recovery [92,93]. Additionally, yogurt is rich in calcium, magnesium, and potassium, all of which support bone health and muscle function, aiding in muscle contractions and helping to prevent cramps [93]. The consumption of yogurt has been associated with a range of health benefits, including improved immune function, reduced cholesterol levels, and alleviated symptoms of lactose intolerance [93,94]. Its anti-inflammatory properties also aid in lowering obesity-induced inflammation and improving glucose metabolism, further supporting recovery and overall health [95].

Incorporating dairy products such as milk and yogurt into post-exercise nutrition provides athletes with essential nutrients that promote muscle repair, bone health, and rehydration. These versatile foods can be easily incorporated into smoothies, shakes, or snacks, offering convenient, nutrient-dense options to optimize recovery strategies.

4.2.2. Anti-Inflammatory Foods (e.g., Tart Cherry Juice, Turmeric, and Other Fruit Juices)

Anti-inflammatory foods support athletic recovery by reducing exercise-induced inflammation and muscle soreness, promoting overall health. Tart cherry juice and turmeric are particularly notable for their potent anti-inflammatory properties. Tart cherry juice is rich in anthocyanins, powerful antioxidants that help mitigate oxidative stress and inflammation resulting from intense physical activity. This effect is consistent with findings from other anthocyanin-rich fruits, such as blueberries, which have been shown to elevate post-exercise levels of anti-inflammatory oxylipins, aiding in inflammation resolution and muscle recovery [97]. Polyphenols in various fruits and vegetables, including those found in tart cherry juice, are recognized for their antioxidant and anti-inflammatory effects. However, their efficacy may vary depending on the specific polyphenol and its application [98]. The consumption of natural fruit-derived antioxidants, such as those found in tart cherry juice, is recommended as a safe nutritional approach to protecting muscle cells from excessive reactive oxygen species (ROS) and alleviating delayed-onset muscle soreness (DOMS) [71].

Moreover, bromelain, an anti-inflammatory enzyme in pineapple juice, has demonstrated its ability to reduce inflammation, further suggesting that various fruit juices can offer recovery benefits for athletes [99]. Additionally, while not directly related to tart cherry juice or turmeric, marine bioactive compounds have been noted for their anti-inflammatory properties, underscoring the broader potential of natural compounds in functional foods to support recovery and overall health [5]. By incorporating anti-inflammatory foods such as tart cherry juice, turmeric, and other fruit-based juices into their diets, athletes can significantly enhance recovery, reduce inflammation, improve muscle repair, and support overall athletic performance.

4.2.3. Omega-3 Fatty Acids (e.g., Fish Oil)

Omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are essential for post-exercise recovery, largely due to their significant anti-inflammatory properties, which are vital for athletes and physically active individuals. These fatty acids play a crucial role in modulating the inflammatory response by reducing the production of pro-inflammatory cytokines and eicosanoids, thereby minimizing muscle soreness and stiffness and promoting faster recovery following intense physical exertion [100]. Research has demonstrated that omega-3 supplementation can enhance muscle regeneration and improve physical performance, making it particularly beneficial in managing conditions such as sarcopenia by increasing muscle strength and endurance [33]. In addition to their role in muscle recovery, omega-3 fatty acids also support cardiovascular health by lowering triglyceride levels, reducing blood pressure, improving circulation, and enhancing nutrient delivery to muscles during recovery [101]. In older adults, omega-3

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supplementation, combined with resistance exercise training, has increased resting metabolic rate, boosted fatty acid oxidation, and reduced systemic inflammation, further supporting recovery and performance [102]. Moreover, omega-3 fatty acids contribute to joint health by alleviating pain and stiffness, providing additional benefits for athletes involved in high-impact activities [103].

For optimal intake, athletes can obtain omega-3s through fish oil supplements or by consuming omega-3-rich foods, such as salmon, mackerel, and sardines, while vegetarians and vegans can opt for algae oil as a plant-based source of DHA. Regular consumption of omega-3s not only supports faster recovery and reduces inflammation but also promotes long-term athletic performance and health by enhancing cognitive function, mood stability, and mental clarity—factors critical for both performance and recovery [33,100]. Table 2 highlights the comprehensive role of functional foods in supporting post-exercise recovery, emphasizing their multifaceted contributions to optimizing recovery outcomes.

Table 2. Comprehensive Role of Functional Foods in Post-Exercise Recovery.

Functional Food Name	Functional Food Key Feature	Benefits on Post-Exercise Recovery	Cited References
Tart Cherry Juice	Rich in anthocyanins, antioxidant properties	Reduces muscle soreness, accelerates recovery, mitigates oxidative stress	Kimble et al. [19], Nieman et al. [97], Nieman et al. [96]
Turmeric (Curcumin)	Contains curcumin, anti-inflammatory compound	Reduces muscle inflammation, supports joint health, enhances recovery	Wan Nur Zahidah et al. [99], Volpe-Fix et al. [98], Dhiman & Kapri [7], Zhang et al. [39]
Blueberries	High in antioxidants and polyphenols	Reduces inflammation, enhances muscle recovery, promotes antioxidant defense	Nieman et al. [97], Hurst et al. [96], Zhang et al. [49], Lane et al. [28]
Beetroot Juice	Rich in nitrates, enhances blood flow	Improves endurance, enhances blood flow and oxygen delivery to muscles	Lane et al. [28], Trangmar & González-Alonso [32], Evans et al. [30], Tomczyk et al. 101]
Green Tea Extract	Contains catechins, antioxidant properties	Reduces oxidative stress, promotes fat oxidation, improves recovery	Dhiman & Kapri [7], Ballini et al. [83], Hurst et al. [96], Shirreffs & Sawka [12]
Pineapple Juice	Contains bromelain, an enzyme with anti-inflammatory properties	Reduces inflammation, supports muscle recovery, aids digestion	Wan Nur Zahidah et al. [99], Dhiman & Kapri [7], Hurst et al. [96]
Pomegranate Juice	Rich in polyphenols and antioxidants	Enhances recovery by reducing inflammation, supports heart health	Nieman et al. [97], Volpe-Fix et al. [98], Zhang et al. [49], Dhiman & Kapri [7]
Spinach	High in nitrates and vitamins	Enhances blood flow, reduces muscle	Ballini et al. [83], Wan Nur Zahidah et

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		soreness, supports recovery	al. [99], Zhang et al. [49]
Yogurt	Contains probiotics and calcium	Supports gut health, aids digestion, enhances muscle recovery	Hadjimbei et al. [93], Yao [92], Hurst et al. [96], Dhiman & Kapri [7], Kaufman et al. [22]
Ginger	Contains gingerol, anti-inflammatory properties	Reduces muscle soreness, enhances anti-inflammatory response	Ballini et al. [83], Wan Nur Zahidah et al. [99], Volpe-Fix et al. [98], Zhang et al. [49], Hurst et al. [96]
Fish Oil (Omega-3 Fatty Acids)	Anti-inflammatory; contains EPA and DHA	Reduces inflammation, promotes faster muscle repair and recovery	Fernández-Lázaro et al. [33], Tomczyk et al. [101]

5. Comparing Food Supplements and Functional Foods

5.1. Nutritional Efficacy

5.1.1. Protein and Muscle Recovery

Both food supplements and functional foods are integral to post-exercise muscle recovery, primarily through their provision of protein. Protein supplements, such as whey and casein, offer a concentrated and rapidly absorbed source of essential amino acids, critical for muscle protein synthesis and repair. Whey protein, mainly, is highly effective when consumed during the "anabolic window" following exercise due to its high biological value and rapid absorption rate [14,104].

In contrast, functional foods, such as dairy products (e.g., milk and yogurt), offer comparable benefits by providing a natural source of protein that supports muscle repair over an extended period. This is primarily due to the slower digestion rate of casein, which allows for a sustained release of amino acids, facilitating prolonged muscle recovery [50,91,92,95]. Moreover, functional foods often contain additional nutrients, such as calcium and vitamin D, essential for bone health and contribute to long-term recovery [89,93].

5.1.2. Anti-Inflammatory and Oxidative Stress Management

Supplements such as antioxidants, including vitamins C and E, and omega-3 fatty acids, are frequently utilized to alleviate oxidative stress and inflammation following intense physical activity [11,71,86,97]. These compounds play a critical role in counteracting the damage caused by free radicals, thereby facilitating more efficient recovery.

Similarly, functional foods such as tart cherry juice, turmeric, and polyphenol-rich fruits offer comparable anti-inflammatory effects, though they are typically consumed as part of a regular diet [19,20,97,98]. The key advantage of functional foods in this context is their comprehensive nutritional profile, which addresses inflammation and provides additional vitamins, minerals, and fiber, contributing to overall health and well-being beyond the scope of inflammation management.

5.2. Practicality and Usage

5.2.1. Convenience of Food Supplements

Food supplements are often preferred for convenience, particularly by athletes with elevated nutrient demands and demanding schedules. These supplements provide a quick and efficient means of achieving specific nutritional targets, such as adequate protein, electrolytes, or creatine intake,

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which may be difficult to obtain solely through whole foods [13,73]. However, there are concerns that over-reliance on supplements could lead to neglecting a balanced diet rich in whole foods, which offer a broader range of nutrients and associated health benefits [105].

5.2.2. Sustainability of Functional Foods

In contrast, functional foods promote a more holistic approach to nutrition, contributing to both recovery and long-term health through consistent dietary consumption. These foods support various aspects of health, such as digestive health through probiotics and cardiovascular health via omega-3 fatty acids, while also offering anti-inflammatory benefits. This makes functional foods a sustainable and advantageous option for both athletes and the general population [32,83,85,87,101]. However, their effects may be less immediate and targeted than food supplements, specifically formulated to meet particular nutritional needs in concentrated forms.

5.3. Risks and Limitations

5.3.1. Over-Reliance on Supplements

Although supplements offer significant benefits, excessive use can result in adverse effects, including gastrointestinal discomfort or nutrient imbalances, particularly with fat-soluble vitamins such as A, D, E, and K [79,82]. Moreover, the lack of rigorous regulatory oversight within the supplement industry raises concerns regarding product purity and quality, posing potential risks for consumers [106].

5.3.2. Functional Foods and Accessibility

While generally safer and less susceptible to misuse, functional foods may not always deliver the specific nutritional support required by athletes involved in high-intensity training [107]. Furthermore, the natural variability in nutrient composition and slower absorption rates can limit their effectiveness when immediate recovery is critical [13,109]. Table 3 comprehensively compares food supplements and functional foods, emphasizing their nutritional efficacy, practicality, usage, and associated risks and limitations.

In conclusion, food supplements and functional foods play essential roles in post-exercise recovery, addressing different nutritional needs. Food supplements offer concentrated nutrients for immediate benefits such as muscle repair and electrolyte replenishment. In contrast, functional foods provide a sustainable approach to recovery and long-term health through bioactive compounds like anti-inflammatory agents and probiotics. Athletes should adopt a balanced strategy for optimal performance and well-being, using supplements to meet acute demands and functional foods to support ongoing recovery and overall health. This approach ensures the body receives both immediate and long-term nutritional support.

Table 3. Comparing Food Supplements and Functional Foods.

Aspect	Comparison	Cited References
Nutritional Efficacy	Food Supplements: Rapid concentrated protein absorption (e.g., whey/casein) for muscle protein synthesis post-exercise.	Gu [14], Snijders et al. [104], Dreyer et al. [27], White [26], Bonilla et al. [3]
	Functional Foods: Natural sources like dairy provide extended recovery with broader nutrients (e.g., calcium, vitamin D).	Zhao et al. [50], Lorinczova et al. [89], Zhang et al. [92], McGlory et al. [35], Chargé & Rudnicki [25]

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Anti-Inflammatory & Oxidative Stress	Food Supplements: Antioxidants (vitamins C, E) and omega-3 supplements reduce inflammation and oxidative stress.	Kaspy et al. [11], Bieńkowski et al. [71], Srinivasan [86], Nieman et al. [97], Carey et al. [130]
	Functional Foods: Polyphenol-rich foods (e.g., tart cherry, turmeric) reduce inflammation with additional vitamins, minerals, and fiber.	Kimble et al. [19], Nieman et al. [97], Carey et al. [98], Wan Nur Zahidah et al. [99], Tomczyk et al. [101]
Practicality & Usage	Food Supplements: Convenient for athletes needing quick nutrient solutions (e.g., protein, electrolytes, creatine).	Abbott et al. [13], Bonilla et al. [73], Kaufman et al. [22], Ballini et al. [83]
	Functional Foods: Sustainable nutrition promoting long-term recovery and overall health, including probiotics for digestive health.	Carey et al. [32], Wan Nur Zahidah et al. [85], Dhiman & Kapri [7], Zhang et al. [39]
Risks & Limitations	Food Supplements: Overuse can lead to side effects, nutrient imbalances, and issues with regulation and purity.	Sandkühler et al. [79], Bonilla et al. [82], Kaufman et al. [106], Forbes et al. [67]
	Functional Foods: May lack targeted support for high-intensity athletes, and natural variability in nutrients can limit effectiveness.	Carey et al. [107], Trangmar & González-Alonso [109], O'Connor et al. [13], Hurst et al. [96]

6. Future Directions and Emerging Perspectives

6.1. Innovations in Recovery Nutrition

6.1.1. Personalized Nutrition Plans Based on Genetic and Metabolic Profiling

The future of recovery nutrition is evolving towards a more personalized approach, driven by advancements in genomic and metabolic testing that enable the creation of individualized nutrition plans. Personalized nutrition considers an individual's unique genetic and metabolic profiles, optimizing health and performance by addressing specific dietary needs and potential deficiencies that traditional assessments might overlook [110,111]. This development is part of a broader shift towards personalized medicine, emphasizing individual differences' importance in health management [112]. By utilizing biomarkers and performance assessments, tailored health plans can be developed to help individuals effectively achieve their wellness goals [113]. Metabolomics plays a crucial role in this process by providing insights into unique metabolic profiles and facilitating the design of nutrition strategies tailored to an individual's specific requirements [111]. As precision nutrition advances, it promises to improve recovery outcomes by ensuring dietary recommendations are scientifically grounded and customized to each individual's needs [114]. This approach significantly advances how nutrition is applied to recovery contexts.

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(1) Genetic Profiling: Genetic testing is critical in identifying individual variations in nutrient metabolism, which can significantly influence dietary recommendations for optimal health. Integrating genetics and metabolomics into personalized nutrition strategies enables the identification of single nucleotide polymorphisms (SNPs) that affect nutrient metabolism and health outcomes, providing a comprehensive approach to personalized dietary interventions [112]. For instance, genetic variants in the vitamin D receptor (VDR) gene may influence metabolic pathways, impacting conditions such as type 2 diabetes and metabolic syndrome. However, the full extent of these effects remains under investigation [115]. Moreover, genotype-based nutritional supplementation has demonstrated that genetic variations can alter the metabolism of nutrients such as vitamin D, iron, and calcium, underscoring the importance of personalized nutrition for improving nutrient absorption and utilization [116]. In nutrigenomics, vitamin D serves as a key example, with its interaction with the VDR modulating gene expression across various tissues, influencing metabolism, bone formation, and immune function [117]. Nutrigenomics further explores how genetic variations influence nutrient-mediated pathways, offering insights into optimizing health and preventing disease through tailored dietary practices [118]. Understanding genetic differences is essential for developing personalized nutrition plans that cater to individual metabolic needs, enhancing nutrient absorption and health outcomes..

(2) Metabolic Profiling: Metabolic profiling involves analyzing an individual's metabolic responses to various foods and nutrients. The concept of metabotyping, which groups individuals based on their metabolic profiles, has improved dietary quality and lipid profiles compared to generalized dietary advice [111,119]. This approach, supported by omics technologies such as metabolomics, provides detailed insights into metabolism by measuring metabolites that reflect food intake and the effects of diets on endogenous metabolism [110]. These technologies enable the identification of clinically relevant subgroups, or metabotypes, allowing for personalized dietary recommendations that may improve adherence to healthier diets and health outcomes [110,119]. By understanding these metabolic responses, customized nutrition plans can be developed to optimize recovery and overall health.

(3) Microbiome Analysis: The gut microbiome is vital in nutrient absorption, immune function, and inflammation regulation. Microbiome-based therapies, such as fecal microbiota transplantation and probiotics, are essential for managing lower gastrointestinal diseases by regulating gut microbiota and microbial compounds that influence disease development and immune responses [120]. These findings highlight the importance of incorporating microbiome analysis into personalized nutrition plans, which can recommend appropriate probiotics and prebiotics to support gut health and enhance recovery.

6.1.2. Advances in Food Technology and Supplement Formulation

Advancements in food technology and supplement formulation are driving innovation in recovery nutrition, enabling the creation of more effective, bioavailable, and convenient products tailored to the needs of athletes and active individuals.

(1) Enhanced Bioavailability: One of the key challenges in nutrition is ensuring that the body effectively absorbs and utilizes consumed nutrients. Nanotechnology facilitates the encapsulation of bioactive agents in colloidal delivery systems designed to protect and deliver nutrients in a bioavailable form, enhancing personalized nutrition products tailored to individual needs such as genetics and lifestyle [121]. Lipid-based nanocarriers, including liposomes and niosomes, improve the intestinal absorption of nutraceuticals by solubilizing them in the intestinal environment and facilitating lymphatic transport, thereby addressing challenges related to poor bioavailability and degradation in the gastrointestinal tract [122]. Nanotechnology in nutrient delivery systems also addresses issues related to the solubility and stability of nutraceuticals, such as curcumin and vitamins, improving their oral bioavailability and reducing first-pass metabolism [123]. Furthermore, nanoparticle technology is being explored for micronutrient fortification in food crops, such as vitamin B12, to combat deficiencies and enhance nutrient delivery without genetic modification, contributing to a more sustainable food system [124]. These innovations improve nutrient delivery

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efficacy while reducing the risks associated with higher doses, marking a significant advancement in nutrition and health care [125].

(2) Functional Ingredients: New functional ingredients are being developed and incorporated into food and supplements to enhance recovery. Plant-based functional foods, such as those containing soy protein, are gaining attention for their potential to provide complete amino acid profiles and reduce inflammation and oxidative stress, both of which are critical in preventing metabolic diseases like diabetes and obesity [126,127]. Soybean proteins, including peptides like lunasin, have demonstrated promising antioxidant and immunomodulatory properties, suggesting their role in functional foods promoting health and preventing oxidative stress-related diseases [127]. Additionally, incorporating plant-based proteins and bioactive compounds into functional foods addresses the rising need to prevent lifestyle-related diseases and promote overall well-being [128]. Novel antioxidants, such as those found in tart cherry and omega-3 fatty acids, have been identified as effective in reducing exercise-induced muscle damage (EIMD) by mitigating oxidative stress and inflammation, thereby enhancing post-exercise recovery [129]. As the market for functional foods expands, continued research and innovation are essential to validate health claims and develop consumer-focused products that meet the growing demand for health and wellness solutions [128].

The future of recovery nutrition is set to make significant strides through personalized nutrition plans and advances in food technology. By utilizing genetic and metabolic profiling, nutrition can be tailored to the unique needs of each individual, optimizing health and performance. Moreover, advancements in supplement formulation and the development of functional ingredients are paving the way for more effective and convenient products that support recovery. As these trends evolve, athletes and active individuals can access more precise and practical tools to enhance their recovery and overall well-being.

6.2. Potential Research Areas

6.2.1. Identifying New Functional Foods with Recovery Benefits

The exploration and identification of novel functional foods with potential recovery benefits represent a promising area for future research. Scientists continue to discover and investigate foods rich in bioactive compounds that promote both athletic recovery and overall health [130]. Emerging superfoods such as moringa, spirulina, and baobab may serve as new sources of essential nutrients and antioxidants, offering recovery benefits through their ability to reduce inflammation, enhance immune function, and support muscle repair [131]. Additionally, the study of traditional foods from various cultures—such as medicinal plants and herbs utilized in Ayurveda, Traditional Chinese Medicine, and Indigenous healing practices—may reveal unique bioactive compounds that contribute to modern nutritional strategies [132]. Focused research on specific bioactive compounds, such as polyphenols, flavonoids, and peptides, can help elucidate their roles in recovery. Understanding how these compounds interact with physiological processes at the molecular level may lead to the development of targeted functional foods.

6.2.2. Long-Term Effects of Regular Use of Food Supplements and Functional Foods

Investigating the long-term effects of regular use of food supplements and functional foods is essential to understanding their sustained impact on health and performance. While the short-term benefits of supplementation are well-established, long-term studies are needed to provide insights into the safety, efficacy, and overall health outcomes associated with prolonged consumption [133]. These studies could determine whether regular use of specific supplements or functional foods reduces the risk of chronic conditions such as cardiovascular disease, diabetes, and osteoporosis, ultimately contributing to prolonged athletic careers and improved health. Furthermore, research into the long-term effects on nutrient absorption and utilization is necessary to identify potential issues such as nutrient imbalances or deficiencies, particularly concerning fat-soluble vitamins and minerals that may accumulate in the body over time. Understanding whether the benefits observed from short-term use are sustained with prolonged consumption, as well as examining any potential

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adaptations in the body's response, is crucial. Evaluating long-term supplement use's safety and possible side effects will help refine dosage recommendations and identify risks associated with prolonged intake.

6.2.3. Interactions between Different Nutritional Strategies

Research into the interactions between various nutritional strategies is critical for optimizing both recovery and performance. This area of study focuses on how different dietary components and the timing of intake influence one another and affect the overall efficacy of nutritional interventions. Investigating the synergistic effects of combining supplements and functional foods may reveal combinations that enhance recovery. For example, combining omega-3 fatty acids with antioxidant-rich foods could amplify their anti-inflammatory benefits [32,64,72]. Research into nutrient timing—such as pre-workout, intra-workout, and post-workout consumption—can offer insights into the optimal timing for specific foods and supplements to maximize recovery [13,14,23]. Furthermore, examining how various dietary patterns, such as ketogenic, vegetarian, or intermittent fasting, interact with supplements and functional foods will allow for the customization of nutrition plans to better suit individual needs and preferences. Understanding how the presence of certain foods or nutrients affects the bioavailability and absorption of others is also critical. For instance, research into how dietary fats influence the absorption of fat-soluble vitamins could lead to more effective supplementation protocols.

7. Conclusions

Nutrition is paramount in post-exercise recovery, significantly influencing muscle repair, inflammation reduction, and overall athletic performance. This review highlights the critical role of food supplements and functional foods in enhancing recovery. Proper nutrition replenishes glycogen stores, repairs muscle tissue, reduces inflammation, and supports the immune system, with nutrient intake timing and quality being crucial for maximizing benefits. Food supplements, such as protein supplements for muscle repair and growth, omega-3 fatty acids for their anti-inflammatory effects, and electrolyte supplements for maintaining hydration, offer significant benefits. Functional foods like tart cherry juice, turmeric, probiotics, leafy greens, and berries provide antioxidants, anti-inflammatory properties, and support for gut health and immune function. Genetic and metabolic profiling advances are paving the way for personalized nutrition plans, while research into synergistic effects and nutrient timing continues to refine recovery strategies. Combining targeted supplementation with a diverse diet rich in functional foods offers a holistic approach to health and performance, helping athletes enhance recovery, support long-term health, and achieve peak performance. Future research and advancements in personalized nutrition will continue to offer even more tailored and effective solutions for recovery and overall well-being.

Integrating supplements and functional foods into an athlete's diet can significantly enhance recovery and performance. Athletes should maintain a balanced diet rich in antioxidants, anti-inflammatory compounds, and essential nutrients from whole foods like leafy greens, berries, fatty fish, nuts, and seeds, supplemented strategically with protein powders, omega-3 fatty acids, and electrolyte tablets, especially during intense training periods. Timely nutrient intake optimizes muscle repair and glycogen replenishment, particularly within 30 minutes to 2 hours post-exercise. Proper hydration with water and electrolyte supplements is crucial, particularly in hot and humid conditions. Genetic and metabolic profiling can further tailor nutrition plans to individual needs. Coaches should educate athletes on nutritional importance, monitor dietary intake with nutritionists, and develop comprehensive, personalized nutrition plans. Nutritionists should regularly assess nutritional status, recommend high-quality supplements, and emphasize functional foods, using genetic and metabolic profiling to create and adjust customized plans. By implementing these recommendations, athletes, coaches, and nutritionists can collaboratively enhance recovery and performance through a balanced approach that includes food supplements and functional foods, supporting muscle repair, reducing inflammation, maintaining hydration, and optimizing overall health while staying informed of the latest nutritional research and advancements.

The evolving landscape of recovery nutrition offers promising opportunities for enhancing athletic performance and overall health. As scientific understanding deepens, integrating food supplements and functional foods has significantly improved muscle repair, reduced inflammation, and optimized recovery. Personalized nutrition, informed by genetic and metabolic profiling, is gaining prominence, enabling tailored nutrition plans for individual athletes. Food technology and supplement formulation advancements are improving the efficacy and bioavailability of recovery products. Research into the long-term effects of supplements and functional foods and their interaction with various dietary patterns and nutrient timing is crucial for developing comprehensive recovery protocols. Continued exploration of emerging superfoods and traditional foods may uncover new bioactive compounds with potent recovery benefits. In conclusion, the future of recovery nutrition is bright, offering numerous possibilities for athletes to achieve optimal recovery, long-term health, and peak performance through informed and holistic strategies.

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