INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

OPEN ACCESS

Review Paper

Significance Of Functional Food in Sports Nutrition and Muscle Recovery

Dr Swati Prakash*, Shantanu Kumar, Vishakha Jaiswal,

Amity Institute of Pharmacy, Amity University Uttar Pradesh, Lucknow Campus, Lucknow- 226028, India..

ARTICLE INFO

Published: 20 Apr 2026
Keywords:
Sports Nutrition , Muscle Recovery, Functional Food, athletic performance
DOI:
10.5281/zenodo.19661826

ABSTRACT

Sports nutrition is important in improving athletic performance, optimum health, and fast recovery of muscles after physical exercise. Over the past few years, there has been a growing focus on functional foods because they are able to offer healthier benefits in addition to basic nutrition. Bioactive components in functional foods include antioxidants, polyphenols, omega-3 fatty acids, probiotics, vitamins, minerals and high-quality proteins, which have a significant role in the performance of exercise and recovery following the exercise. The typical effects of hard training include muscle damage, inflammation, oxidative stress, and delayed onset muscle soreness (DOMS), hence the importance of proper nutritional approaches to athletes and physically active people.In this review we discuss about the benefits of functional foods in the provision of energy needs, endurance, immune responses, inflammation, reduced oxidative stress, and muscle protein synthesis. Dairy products, whole grains, fruits, vegetables, omega-3-rich foods, probiotics, turmeric, ginger, and tart cherry juice are specific functional foods which are emphasized to have a positive effect on muscle repair and recovery.Moreover, this review compares the functional foods and the traditional sports supplements based on their safety, natural source, and health implications in the long term. Although these advantages exist, there are also challenges that are considered including bioavailability, individual difference as well as regulatory challenges. All in all, functional foods are a quite promising and viable prospect to sports nutrition and muscle recovery. In sports science, the combination of them into normal dieting practices can result in the improved performance of athletes, faster recovery, and their overall health, which makes the need to conduct more research and custom-designed nutrition plans as a priority..

INTRODUCTION

1.1 Concept of Sports Nutrition and Its Importance in Athletic Performance

***Corresponding Author:** Dr Swati Prakash
Address: *Amity Institute of Pharmacy, Amity University Uttar Pradesh, Lucknow Campus, Lucknow- 226028, India*
Email ✉: sprakash@lko.amity.edu

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Sports nutrition is a specific branch of nutrition science that deals with the maximization of dietary intake to promote athletics performance, physical conditioning and the effective post-exercise recovery. Nutrition is critical in providing enough energy to address the heightened energy needs, fluid and electrolyte balance, and in aiding the metabolic adjustments during training and competitions(1). Carbohydrates are macro nutrients that are important in supplying energy to sustain long term workouts, proteins are used to repair and build muscle protein and fats are used as secondary sources of energy during the long-term aerobic exercises. Along with them, micronutrients, antioxidants, and other bioactive compounds have an impact on the immune functioning, oxidative stress reactions, and the general health condition of athletes. There has been evidence that individual nutrition plans could enhance endurance, strength, and recovery which are also major elements of athletic success(2).

1.2 Muscle Fatigue, Injury, and Recovery in Sports Activities

Exercise-induced muscle damage (EIMD) is frequently observed to be caused by intensive physical exercise, including muscle fatigue, structural damage, inflammation, and oxidative stress. The fatigue of muscle is evidenced by loss of performance capacity, on the one hand; on the other hand, is the DOMS (delayed onset muscle soreness) which is a consequence of micro trauma of muscle fibre with a negative consequence of performance should the recovery be insufficient(3). The processes of physiological mechanisms surrounding the effective recovery are a complex interaction of glycogen recovery, critical inhibition of damaged tissue repair through synthesis of proteins, decreasing inflammation, and oxidative balance restoration. Such processes are affected by the availability of nutrients and are important in minimizing risk of injury and in making an individual prepared to be trained again in the future(4).

1.3 Emergence of Functional Foods in Sports Science

Functional foods are considered as such in which they give health advantages beyond standard nutrition because of the presence of bioactive compounds like polyphenols, omega-3 fatty acids, probiotics, prebiotics, vitamins, minerals, and peptides. The foods have generated the interest they have had in the field of sports science on their capability to regulate physiological processes that are pertinent in the exercise performance and recovery. As an illustration, polyphenol-containing foods might have an anti-inflammatory effect on inflammation and oxidative stress, probiotics can improve gut and immune health, and functional omega-3 fatty acids are anti-inflammatory and can lead to an improved recovery outcome [turn0search1]. Several randomized controlled trials (RCTs), systematic reviews, and meta-analyses have investigated the performance, muscle damage indicators, and recovery indicators effects of certain functional food components, indicating they might be useful as supplementary nutritional methods to conventional diets(5).

2. Methodology:

The review study on Significance of Functional Food in Sports Nutrition and Muscle Recovery was done through structured and systematic literature search. The most significant databases, such as PubMed, ScienceDirect, Scopus and Google Scholar, were used to identify relevant scientific studies to cover all evidence available.The following Boolean operators (AND/OR) were applied to a combination of keywords that included: functional foods, sports

nutrition, muscle recovery, exercise-induced muscle damage, bioactive compounds, randomized controlled trials, systematic reviews, and mechanistic studies. Peer-reviewed articles in the English language published until January 2026 were included in the search.The inclusion criteria included randomized controlled trials (RCTs), observational studies of athletes, systematic reviews, meta-analyses, and experimental (animal and in-vitro) mechanistic studies that provided the outcomes of the effects of functional foods or bioactive food components on muscle recovery, oxidative stress, inflammation, muscle protein synthesis, mitochondrial activity, or performance outcomes. Articles that were not in the fields of sports nutrition and did not have the relevant outcome measures were omitted.

3. Overview of Sports Nutrition

3.1 Energy Requirements in Athletes

The direct relationship between the optimal sports performance and the capability of the athlete to require high energy levels demanded by the training and competition practices is undeniable. Athletes require substantially much more energy than people who are not involved in any physical activity do, and insufficiency of energy intake results in fatigue, low performance, and poor recovery. The total daily energy expenditure (TDEE) of athletes depends on the type of sport, intensity, duration of training, and physiological specifics, and is sometimes up to 2000-5000kcal/day in high-level athletes. The adequate supply of energy will facilitate metabolism, immune system, hormonal balance and training adaptation.(3)

3.2 Role of Macronutrients

Proteins in Muscle Synthesis

Muscle protein synthesis (MPS) cannot occur without proteins. Amino acids that are contained in diet proteins trigger MPS after resistance or endurance training they aid in the repair of muscle injuries caused as a result of exercise. Study shows that co-intake of proteins with carbohydrates can lead to better performance results (time-to-exhaustion, probably via better glycogen storage and MPS). Proper protein consumption also averts adverse nitrogen status that will subsequently cripple training potential and cause loss of lean mass.(4)

Carbohydrates in Glycogen Replenishment

In muscles and liver, carbohydrates are stored in the form of glycogen, which is the most easily accessible source of energy in the face of high intensity exercise. The breakdown of glycogen is directly linked to fatigue and deterioration of performance. Glycogen stores are important to the athlete because they are replenished at a rapid pace during the post-exercise period of the day, or on consecutive days of competing. The reviews on sports nutrition have shown that the post-exercise consumption of carbohydrates together with proteins is more effective in glycogen resynthesis and recovery than carbohydrates alone. This is especially applicable in a sport that involves high intensity activities like repetition.(5)

Fats in Endurance Sports

Fats are not the quickest energy source to metabolize as compared to carbohydrates but happen to be a significant energy source during low to moderate intensity exercise as well as during prolonged exercise. Fat oxidation is becoming more important in endurance athletes to maintain 5the minimal amounts of glycogen supplies, extend the length of performance, and delay fatigue. An appropriate consumption of required fatty acids also contributes to anti-

inflammatory mechanisms and integrity of cell structure. The necessary level of fat intake is also necessary to absorb fat-soluble vitamins (A, D, E, K) that also lead to physiological resilience in athletes.(6)

3.3 Role of Micronutrients

Vitamins (B-complex, C, D, E)

vitamins B-complex play an important role in energy metabolism, which helps the body to break down carbohydrates, fat and protein to provide energy.Vitamins C and E are antioxidants and they aid in the reduction of oxidative stress during intense training. vitamin D is necessary when it comes to muscle functioning and immune system. The lack of these vitamins may suppress the performance, adaptation, and recovery especially in cases where the energy consumption is inadequate.(7)

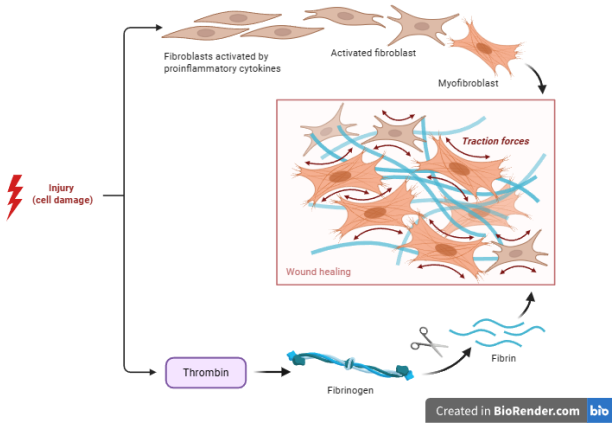
Minerals (Iron, Calcium, Magnesium, Zinc)

Minerals are critical in the transfusion of oxygen (iron), local bone formation and muscular contractions (calcium and magnesium), enzymatic activities and immune functions (zinc). The role of iron in endurance athletes is especially significant because of the intrinsic part of hemoglobin development and oxygen transportation iron deficiency may result in the development of anemia and decreased aerobic capacity. Calcium and magnesium also play a role in neuromuscular activity and electrolyte balance and zinc aids in protein synthesis and immune system.(8)

4. Muscle Damage and Recovery Mechanisms

4.1. Muscle Structure and Function

Muscle tissue is a special type of connective tissue that produces movement, postures and force in the human body. The skeletal muscle is the most significant muscle tissue of the three, which are skeletal, cardiac, and smooth. Skeletal muscles are voluntary muscles which are connected to bones with the help of tendons and make it possible to move the body in case of an exercise or sportive activity.(9)



Structure of Skeletal Muscle

The skeletal muscle is hierarchically arranged. The bundles of muscle fibres are called fascicles that are enclosed by layers of connective tissues and that form each muscle. The epimysium is the outermost layer, which covers the whole muscle; perimysium is surrounding each fascicle; endomysium is surrounding each muscle fibre. This is a structural connective tissue network that offers support and aids in conduction of force produced in contraction.

Every muscle fibre is a long, cylindric multi-nucleated cell that contains hundreds of myofibrils. The myofibrils consist of repeating functional units referred to as sarcomeres which are the fundamental units of contraction in muscle. The Sarcomeres are mainly made up of two different protein types, which include actin (thin filaments) and myosin (thick filaments). These filaments are organized in a structured manner and it is this structure that makes skeletal muscle appear striated.(10)

Function of Skeletal Muscle

Skeletal muscle has the main role of generating motion and force in its contraction of the muscle. Contraction of the muscle is through sliding filament mechanism whereby myosin head attaches itself to actin filament and drags them towards the center of the sarcomere causing the muscle fiber to shorten. This process needs energy in the form of adenosine triphosphate ATP.Skeletal muscles also are important in maintaining the posture and stability of the joints particularly in dynamic and intensive sports exercises. Moreover, skeletal muscle can be considered as a large energy storage and metabolism location, and it houses glycogen, as well as it is involved in glucose regulation during exercise. Heat is also generated by the contraction of muscles to aid in the regulation of body temperature.(11)

4.2 Exercise-Induced Muscle Damage (EIMD)

Causes of Muscle Damage

EIMD usually happens when exercising in an unfamiliar or intense-intensity, particularly eccentric-contraction exercise (e.g. downhill running, resistance training) that subject the muscle fibres to mechanical loads that are greater than the structural limits of the muscle fibres. This causes cytoskeletal dysregulations, sarcolemma rupture, calcium homeostasis derailment and protease and inflammatory-mediated pathways and causes leakage into circulation of muscle proteins and diminished force generation**.**

Delayed Onset Muscle Soreness (DOMS)

DOMS represents the pain and the stiffness experienced 1-3 days after strenuous activity, reaching its peak at 24-72 hours. It is linked to microtrauma, temporary inflammation, and excess metabolism by-products in the impaired tissues. The inflammatory flow encompasses the stimulation of neutrophils and macrophages which remove cell debris and secrete cytokines that cause soreness sensations. DOMS is another indication that the process of remodeling muscle has been triggered which is critical to adoption and strengthening.(12)

4.3 Muscle Repair and Regeneration

Protein Synthesis

The process of muscle protein synthesis (MPS) provides a significant contribution to muscle protein synthesis, which is the process of assembly of amino acids into new proteins necessary to restore damaged muscle fibers. This process is increased following resistance and endurance exercise and it is also augmented by proper nutrition and rest. MPS plays a crucial role in repairing, as well as, adapting and hypertrophying muscle tissue. Resistance training enhances the ability to remodel muscle following damage and improves its efficiency and capacity due to translational capacity.(13)

4.5 Inflammatory Response

The first stage of muscle repair entails tightly controlled inflammatory response. Pro-inflammatory (M1) and anti-inflammatory (M2)

macrophages invade early and late respectively to clear necrotic debris and activate tissue repair and reduce inflammation respectively. This two-stage reaction promotes successful re-generation and inhibits too much tissue breakdown.

4.6 Role of Satellite Cells

The quiescent stem-like cells between the sarcolemma and basal lamina of muscle fibers are known as satellite cells. When they are activated by mechanical stress or damage, they grow, develop into myoblasts and fuse with existing fibers or generate new fibers thereby leading to growth and repair of muscles. Activation of satellite cell is a necessary process that leads to successful regeneration, particularly following severe damage, and is dependent on nutrient availability and exercise stimuli.(14)

5. Functional Foods: Concept and Classification

Functional Foods:

Functional foods are those that have health-promoting effects above the normal level of nutrition, as a result of the availability of bioactive compounds that can change physiological functions and lessen the risk of diseases when they are ingested during normal diets. These are not regular diet products as they have compounds that are actively involved in regulating metabolic processes, immune work, inflammation, or the makeup of microbiota, and not simply an energy source as a source of macronutrients and calories.(15)

Classification of Functional Foods

Functional foods can be classified into the following major categories based on their origin and mode of modification:

1.Natural Functional Foods: They are natural whole foods that contain health promotional bioactive compounds. Examples are fruits (berries, apples), vegetables (broccoli, spinach), nuts, seeds, fish (which is rich in omega-3 fatty acids), fermented foods (kefir, kimchi) and whole grains. These foods naturally have phytochemicals, antioxidants, fatty acids, fibers and micronutrients which are health beneficial without deliberate fortification.

2. Fortified/Enriched Foods: Fortified or enriched functional foods are ordinary foods that have undergone fortification by the addition of nutrients or bioactive proteins to their original composition to acquire desired health effects. Another typical example is milk that is fortified with vitamin D, breakfast cereals that are fortified with omega-3 fatty acids, and yogurt with probiotics added to it. Fortification tries to enhance certain health consequences, e.g. bone health, cardiac health, or gut performance.(16)

3. Probiotic and Prebiotic Foods: These consist of foodstuffs with live useful microorganisms (probiotics) or character that selectively provides stimulation to advantageous gut bacteria (prebiotics).

Probiotics foods usually contain fermented dairy items in Lactobacillus or Bifidobacterium species that give gastrointestinal and immunological health advantages to the body.

Prebiotic foods include non-digestible fibers (e.g., inulin, fructo oligosaccharides) which enhance the growth and activity of healthy gut microbiota which helps with digestion and metabolism.

. Bioactive Compound-Rich Foods: These are foods that particularly contain high amounts of bioactive molecules (polyphenols, flavonoid, carotenoids, phytosterol, omega-3 fatty acid, and

antioxidant vitamin). This type encompasses foods containing condensed health-promoting substances that affect cellular activities, inflammation and oxidative stress.(17)

5.2 Bioactive Components in Functional Foods

Functional foods owe their health benefits to specific bioactive components that exert physiological effects:

Polyphenols are a large group of phytochemicals found in fruits, vegetables, teas, cocoa, and seeds. These compounds have antioxidant, anti-inflammatory, and cardioprotective properties. Systematic reviews and mechanistic studies indicate that polyphenols can modulate oxidative stress, cellular signaling, and immune responses, which are relevant for recovery in physically stressed athletes.(18)

Omega-3 Fatty (e.g., EPA and DHA) are found in fatty fish, flaxseeds, and fortified foods. These compounds exhibit anti-inflammatory effects, regulate lipid metabolism, and support cardiovascular health. Omega-3s have been studied in clinical trials for their effects on inflammatory markers post-exercise, muscle soreness, and recovery processes.

Antioxidants include vitamins (A, C, E), flavonoids, carotenoids, and plant polyphenols. These agents neutralize free radicals, reduce oxidative stress, and protect cellular structures from damage. Clinical evidence supports their role in modulating the body's stress response and enhancing recovery after strenuous exercise.(19)

Peptides and Amino Acids derived from proteins can influence metabolic pathways, satiety, immune function, and muscle repair. Certain peptides released during digestion or fermentation have antihypertensive, antioxidant, and immune-modulating effects. Protein-derived amino acids such as leucine play key roles in muscle protein synthesis, making them important components of functional foods targeting recovery.(20)

6. Role of Functional Foods in Sports Nutrition

6.1 Functional Foods for Energy Enhancement

Whole grain: Complex carbohydrates, dietary fiber, and micronutrients are abundant in whole grains (e.g., brown rice, oats, quinoa), which is why these products are the best energy sources. Whole grains also have slow glucose release, which stabilizes the blood sugar and provides sustained energy to the body during extended exercise, unlike refined carbohydrates. They are also rich in fiber and micronutrient which helps in maintaining general health of metabolism which indirectly affects performance and recovery.

Fruits and Natural Carbohydrates: Fruits have simple carbohydrates (glucose, fructose) that are quickly assimilated and contain immediate energy to train and compete. Pre-exercise meals may also include fruits like bananas and dates to replenish the glycogen stores and delay fatigue. Also, their vitamins and antioxidants reduce oxidative stress that is caused during exercise.(21)

Beetroot Juice and Nitrates: Beetroot juice is a functional food that contains a lot of dietary nitrates (NO3-). After the intake, the nitrates are broken down to nitrite and subsequently to nitric oxide (NO), which dilates blood vessels, decreases the cost of oxygen in the exercise, and improves mitochondrial activity. Recent systematic umbrella review demonstrated that beetroot juice enhances time to exhaustion, VO2max and acute supplementation (2-3 hours before exercise) has best effects on performance in trained and untrained individuals. It is proposed that acute and chronic intake of the optimal doses of nitrate

should be taken to improve physical performance parameters.(22)

6.2 Functional Foods for Endurance and Performance

Omega-3 Rich Foods: Anti-inflammatory foods that contain omega-3 polyunsaturated fatty acids (e.g., salmon, sardines, chia seeds) can influence membrane fluidity that can have a positive effect on muscle recovery, cardiovascular health, and possibly training adaptation. Even though the direct RCT evidence regarding omega-3 intake and its impact on measurable endurance performance has not developed yet, mechanistic information is given about their influence on the reduction of exercise-induced inflammation and recovery.

Caffeine-Containing Foods: Caffeine is a natural stimulant that is present in coffee, tea and some functional drinks. Caffeine improves central nervous system stimulation, catecholamine release and has the ability to spare muscle glycogen which causes better performance especially in endurance races. Position and exercise nutrition review evidence supports caffeine consumption (usually 3-6 mg/kg body weight -60 min prior to exercise) to improve alertness, perceived exertion, and endurance exercise performance.

Electrolyte-Rich Foods: Sodium, potassium, magnesium, and calcium are important electrolytes vital in fluid equilibrium, nerve conduction and muscle contraction. Coconut water, pickles and water enriched with minerals are functional foods used to restore the electrolytes that are lost in sweat. Electrolyte balance helps in maintaining hydration condition and performance particularly during long or hot conditions training.(23)

6.3 Functional Foods in Immune Support for Athletes

Probiotics and Gut Health: Probiotics are live microorganisms, which are present in fermented foods (e.g., yogurt, kefir, kimchi) and are able to regulate gut microbiota and facilitate immune functioning. During high training regimes, athletes usually suffer temporary lapses in immunity and enhancement of susceptibility to infection. According to the evidence provided in several clinical trials and reviews, the regular intake of probiotics might lead to less frequent and less acute upper respiratory symptoms and contribute to recovery, with the help of maintaining the integrity of the gut-immune axis.

Vitamins and Antioxidants: Fruits, vegetables, and green tea are rich in vitamins which have antioxidant effects (vitamin C and vitamin E, polyphenol, etc.). They are important in counteracting the production of free radicals during intensive exercise, oxidative stress as well as recovery of the muscle tissue. A systematic perception on the nutritional aspect of sports emphasizes the essence of antioxidants in mitigating oxidative injury and promoting a general physiological robustness around the periods of excessive training.(24)

7. Functional Foods in Muscle Recovery

Functional foods play a key role in post-exercise recovery by providing nutrients and bioactive compounds that support muscle repair, reduce inflammation, mitigate oxidative stress, and enhance physiological restoration after strenuous activity. Research suggests that targeted consumption of nutrient-rich foods soon after exercise can positively influence muscle recovery outcomes and performance adaptation.

7.1 Protein-Rich Functional Foods

Dairy Products (Whey, Yogurt): Whole proteins in dairy products like whey protein and yogurt are complete sources of proteins with all the essential amino acids, and the protein leucine that acts as a core process to stimulate muscle protein synthesis (MPS) a fundamental step to repair and growth after exercise. Whey is digested quickly, and the level of plasma amino acids increases rapidly, increasing the MPS, but probiotics and micronutrients useful in recovery can also be found in yogurt. It has been demonstrated in RCTs that combined protein and antioxidant supplementation following eccentric exercise is capable of enhancing muscle function and lowering muscle damage indicators, in comparison to carbohydrate controls(25).

Plant-Based Proteins (Soy, Legumes): Soy and legumes are examples of plant proteins that are currently being researched regarding recovery effects particularly in vegetarian and vegan athletes. Soy protein has a complete profile of amino acids, and has been reported to prevent muscle damage during exercise and aid in recovery in case it is taken in adequate daily portions. In case leucine load is sufficient, blends of plant proteins optimized on leucine (e.g., pea + rice) can be equally effective as whey protein in stimulating myofibrillar protein synthesis in RCTs.

7.2 Antioxidant-Rich Foods

Berries, Cherries, Citrus Fruits: Fruits that are rich in polyphenols (e.g., berries, tart cherries, citrus) contain antioxidants which counter reactive oxygen species (ROS) produced by exercise and assist in recovery. The meta-analyses suggest that the use of tart cherry supplement can prevent delayed onset muscle soreness (DOMS) and hasten recovery of muscular strength following intense exercise, and has moderate positive effects on performance measures and inflammatory biomarkers. The systematic evidence indicates the same recovery benefits by the use of polyphenol-rich foods such as pomegranate and beetroot juice through antioxidant and anti-inflammatory pathway(26).

Green Tea and Cocoa: The green tea is a good source of catechins and, in particular, of epigallocatechin gallate (EGCG), which is a potent antioxidant that could be useful in reducing oxidative stress after exercise. The potential effects of cocoa flavanols also include the enhancement of muscle functionality recovery in the post-exercise period, and some studies revealed statistically significant recovery of strength recovery at the 48 hour. The antioxidant foods may be either consumed as drinks or supplemented to the recovery meals to enhance functionality.

7.3 Anti-Inflammatory Functional Foods

Turmeric (Curcumin): The active ingredient present in turmeric is curcumin which possesses anti-inflammatory and antioxidant properties due to its ability to inhibit pro-inflammatory pathways (e.g., COX-2, TNF-a). The clinical research shows that curcumin supplementation before and after strenuous activities lowers markers of inflammation (e.g., CK) and DOMS, which makes it an effective recovery functional food. Greater improvements in bioavailability preparations of curcumin would yield more consistent results on post-exercise-induced inflammation**.(27)**

Ginger: Ginger has anti-inflammatory properties (e.g. gingerols) which can potentially be used to alleviate muscle soreness after exercise, but the effect of this in athletic situations is mixed and needs more controlled trials**.**

Omega-3 Fatty Acid Sources: Healthy fats contain a lot of omegas-3 (fatty fish, sardines, and seeds like flax, chia) and functional foods suppress the effects of inflammatory reactions and membrane activity causing the production of pro-inflammatory cytokines. Mechanistic reviews verify that omega-3s suppress the process of muscle inflammation and can promote recovery processes, but the effects are different in accordance with dose and training conditions.(28)

7.4 Functional Foods for Reducing Muscle Soreness

Tart Cherry Juice: One of the most examined recovery foods is tart cherry juice high in anthocyanins as well as polyphenols. A meta-analysis and systematic review of 14 studies indicate that tart cherry supplementation has a small- to-moderate positive effect on decreasing muscle soreness (DOMS) and recovery of muscular strength and power after exhaustive exercise. These are said to be due to fewer inflammatory signals and increased antioxidant activity.

Pineapple (Bromelain): Pineapple fruit is a source of bromelain, a proteolytic enzyme that is postulated to have anti-inflammatory effect. Even though studies in exercise situations are inconsistent with those in cherries, bromelain can help in recovery by affecting the inflammation and swelling following muscle damaged, although the evidence is inconsistent with dose and injury type(29).

Table: Functional Foods, Bioactive Components, and Their Role in Muscle Recovery

S. No.	Functional food	Bioactive component	Mechanism of action	Benefit in sports	Ref. No.
1.	Dairy (Whey, Yogurt)	Protein, leucine	Stimulates muscle protein synthesis (mTOR pathway)	Muscle repair & growth	(30)
2.	Fatty fish (salmon)	Omega-3 fatty acids	Anti-inflammatory	Reduces muscle soreness	(31)
3.	Berries / Tart cherry	Polyphenols, anthocyanins	Anti-oxidant activity	Reduces DOMS	(32)
4.	Turmeric	Curcumin	Inhibits inflammatory pathways (COX-2, TNF-α)	Faster recovery	(33)
5.	Beetroot juice	Nitrates	Improves blood flow	Enhances endurance	(34)

8. Mechanisms of Action of Functional Foods in Muscle Recovery

8.1 Reduction of Oxidative Stress

In extreme exercise, the high rate of oxygen uptake in muscle cells causes the formation of excessive reactive oxygen species (ROS), which may damage lipids, proteins, and DNA, which cause muscle fatigue and slow recovery. Polyphenols, vitamins C and E, carotenoids, flavonoids and other functional foods demonstrate a strong antioxidant effect that neutralizes ROS to inhibit oxidative damage. Systematic review and meta-analysis demonstrate that polyphenol-containing foods (e.g., berries, cherries, pomegranate) could be used in order to reduce the biomarkers of oxidative stress considerably and restore functional recovery after exercise-induced muscle

damage. On a molecular level, antioxidant compounds stimulate host defense mechanisms like Nrf2/HO-1 increasing the levels of antioxidant enzymes such as superoxide dismutase (SOD) and catalase, which leads to cellular resilience(35).

8.2 Modulation of Inflammation

The process of clearing of the damaged cells and the following repair is an inevitable event in the post-exercise inflammation, however, excessive or chronic inflammation may slow down the recovery process. Inflammatory pathways have been regulated in functional foods containing omega-3 fatty acids, curcumin and flavonoids which inhibit key inflammatory mediators, that is, NF-kB, IL-6, TNF- a and cyclooxygenases enzymes. There is systematic evidence indicating dietary bioactive can induce a shift in macrophage polarization to an anti-inflammatory (M2) to a pro-inflammatory (M1) phenotype to stimulate tissue regeneration as well as restrain undue inflammation. This balance of the inflammatory response assists in balancing the removal of injured tissues and the regenerative mechanisms(36).

8.3 Enhancement of Muscle Protein Synthesis

High-quality proteins and amino acids in functional foods directly trigger muscle protein synthesis (MPS), which is an extremely important process in repairing muscle microtrauma that results following exercise and in hypertrophy. mTOR signaling pathway is activated by whey protein and leucine-rich foods and enhances muscle growth and MPS. Mechanistic evidence indicates that whey protein prevents oxidative stress and improves muscle morphology and function by inhibiting the SIRT1/Nrf2/AMPK/mTOR/4EBP1 axis; thereby preventing oxidative stress, increasing protein synthesis, and subsequently muscle morphology and functioning in exercised rodents. Further, food-derived amino acids supply food-derived substrates to facilitate repair and decrease proteolysis during recovery, which is in support of net muscle protein accretion(37).

8.4 Improvement in Mitochondrial Function

Mitochondria play a crucial role in production of energy and metabolic homeostasis in skeletal muscle. High polyphenol, omega-3 fatty acids and other bioactive functional foods facilitate mitochondrial biogenesis and antioxidant ability, which are triggered by specific regulators, including AMP-activated protein kinase (AMPK) and peroxisome proliferator-activated receptor gamma coactivator-1a (PGC-1a). These pathways increase the density and efficiency of the mitochondria to increase ATP synthesis and decrease the generation of ROS during exercise and recovery. Enhanced mitochondrial activity fastens the recovery of energy in damaged fibers in muscles, which helps an athlete to adjust to performance and minimize fatigue(38).

8.5 Regulation of the Gut–Muscle Axis

New data give credit to the presence of a gut-muscle axis, according to which the gut microbiota can affect muscle metabolism, inflammation and recovery by producing metabolic substances and modifying the immune response. Short-chain fatty acids (SCFAs) secreted by the helpful gut bacteria (e.g. due to the fermentation of dietary fibers and prebiotics) may reach circulation and influence muscle protein anabolism, glucose uptake, and the regulation of inflammation.(39) The exercise by itself changes the composition of gut microbiota, which further impacts muscle functions and metabolic wellbeing. Probiotic and prebiotic functional foods have the potential to improve this axis by enhancing microbial diversity, decreasing systemic inflammation, and enhancing the utilization of nutrients, increasing muscle recovery

and decreasing muscle loss in sarcopenia and exercise stress(40).

9. Evidence from Human Studies

Randomized Controlled Trials (RCTs)

A number of RCTs have examined the efficacy of functional foods, or bioactive compounds therein, on muscle recovery, or exercise-induced muscle damage (EIMD).

Omega-3 Supplementation: In a randomized controlled trial, 3g/day omega-3 polyunsaturated fatty acids lessened muscle soreness at delayed onset and some of the inflammatory responses following EIMD as compared to placebo, but did not affect performance measures.

Polyphenol-Rich Foods: A meta-analysis of 26 RCTs showed that flavonoid-rich polyphenol interventions had a positive effect on recovery of muscle strength and soreness up to 96 h EIMD compared with controls.

Protein Intake: There is systematic evidence that protein supplementation in diet has a significant effect on muscle damage recovery in resistance exercise, improving muscle protein synthesis and with a reduction in signs of muscle damage, relative to no or low protein consumption.

These randomized human trials have solid reasons that functional foods high in omega-3s, polyphenols, and high-quality proteins affect recovery variables such as muscle soreness, muscle recovery, and inflammation after exercise-induced injuries in a positive way.(30)

9.1 Observational Studies in Athletes

Although there are an insufficient number of observational studies that were dedicated to functional foods, research in the field of sports nutrition often includes reports of relationships between regular intake of nutrient-rich foods (e.g., fruits, whole grains, dairy) and better recovery outcomes in athletes. In this type of study, benefits of increased consumption of antioxidants and omega-3 rich foods are generally associated with lower levels of oxidative stress and inflammatory markers after exercise. Functional food the roles of systematic reviews of diet patterns in athletes indicate that greater diversity of whole-food intake is positively associated with sustainable performance and reduced occurrence of overtraining symptoms, indicating functional food functions.(31)

9.2 Evidence from Animal and In-Vitro Studies

Experimental (animal and cellular) research is useful in explaining the mechanism of action of functional food components at the molecular and cellular level:

Anti-Inflammatory and Regenerative Pathways: Mechanistic Reviews Omega-3 PUFAs and their derivatives regulate local skeletal muscle inflammatory signaling, promoting muscle repair and regeneration following injury by changing cytokine profiles and lipid mediators.

Modulation of Oxidative Stress: In Vivo and cellular studies indicate that polyphenols and antioxidant compounds do have the potential to activate endogenous elements of antioxidant response (e.g. Nrf2 pathways), and decreasing oxidative damage in muscle cells following metabolic or mechanical stress.(32)

Protein Metabolism: Cellular models also show that amino acids and bioactive peptides produced by the functional foods interact with muscle protein synthesis pathways, such as the mTOR signaling axis that plays a vital role in muscle repair and adaptation.

These mechanistic concepts are supplementary to clinical data, which reveal that bioactive food ingredients help in muscle recovery on the biochemical rank.

9.3 Comparison with Conventional Supplements

Protein Powders vs Functional Foods.

Efficacy: Meta-analysis reveals that whole-food sources of protein (e.g., dairy, soy) and protein-rich functional foods may also offer the same recovery benefits as isolated protein powders, especially when taken in adequate amounts around training sessions.

Bioavailability & Completeness: Whole foods provide full nutrient profiles that contain co-factors like micronutrients and polyphenols that might act synergistically with amino acids to enhance recovery more holistically compared to isolated protein powders in isolation.(33)

Git and Systemic actions: There are also cases of functional foods such as fermented dairy (yogurt, kefir) and plant mixtures, which can have gut health benefits, which indirectly reflect on immune status and recovery, which is not always the case with conventional supplements.

Safety and Compliance

The safety profile of functional foods is usually high when they are taken in a normal dietary range and are also linked with fewer side effects than high dose isolated supplements. In addition, the athletes are more likely to adhere to dietary plans that include the intake of natural foods as opposed to taking pills or powders, which may be explained by their ease of use and cultural food habits. Nevertheless, timing and the amount is crucial.(34)

Table: Summary of Clinical Evidence on Functional Foods in Muscle Recovery

S. No.	Study type	Functional food	Key finding	Outcome	Ref. No.
1.	RCT	Omega-3	Reduced inflammation & DOMS	Improved recovery	(41)
2.	Meta analysis	Polyphenols	Reduced oxidative stress	Faster strength recovery	(42)
3.	RCT	Whey protein	Increased MPS	Muscle repair	(43)
4.	Systemic review	Tart cherry	Reduced muscle soreness	Enhanced recovery	(44)
5.	Observational study	Whole diet pattern	Reduced injury	Better performance	(45)

CONCLUSION

functional foods are important to sports nutrition and muscle recovery. It has been continually demonstrated through research that protein-rich foods increase muscle protein synthesis, fruits rich in polyphenols decrease oxidative stress, and omega-3 fatty acids and other anti-inflammatory bioactive can be used to regulate exercise-induced inflammation and soreness. The growing evidence also favors the amelioration of mitochondrial activity and regulation of the gut-muscle axis.

Functional foods are whole nutritional because they contain macronutrients, micronutrients, and bioactive compounds in combination, which has benefits over single-supplement nutritional

practices. They do not only result into quicker recovery of muscles and an enhanced performance but also act to support the immune system and the health of athletes in the long run.

In the case of athletes and coaches, whole-food sources of protein sources, antioxidant-rich fruits, omega-3 foods, and probiotic-rich foods can be added to daily foods to improve recovery, minimize muscle damage, and maintain training results. All in all, functional foods are an evidence-based, safe, and practical approach to the optimal of sports recovery and performance.

REFERENCES

1. Bhattarai P, Niroula K, Nirmal NP. Sports nutrition: boosting performance with functional foods. In: Unleashing the Power of Functional Foods and Novel Bioactives. Elsevier; 2025. p. 139–59. doi:10.1016/B978-0-443-28862-3.00008-X
2. Fernández-Lázaro D, Arribalzaga S, Gutiérrez-Abejón E, Azarbayjani MA, Mielgo-Ayuso J, Roche E. Omega-3 Fatty Acid Supplementation on Post-Exercise Inflammation, Muscle Damage, Oxidative Response, and Sports Performance in Physically Healthy Adults—A Systematic Review of Randomized Controlled Trials. Nutrients. 2024 Jun 27;16(13):2044. doi:10.3390/nu16132044
3. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
4. De Zan D, Eletti F, Fiore G, Di Girolamo E, Bozzini GGM, Perico V, et al. Use of Nutritional Strategies, Bioactive Compounds, and Dietary Supplements in Young Athletes: From Evidence to Potential Risks—A Narrative Review. Nutrients. 2025 Jun 30;17(13):2194. doi:10.3390/nu17132194
5. Gonçalves AC, Gaspar D, Flores-Félix JD, Falcão A, Alves G, Silva LR. Effects of Functional Phenolics Dietary Supplementation on Athletes' Performance and Recovery: A Review. Int J Mol Sci. 2022 Apr 22;23(9):4652. doi:10.3390/ijms23094652
6. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
7. Stupin A, Perić L, Jukić I, Boris A, Stanojević L, Drenjančević I. Assessment of Micro- and Macronutrient Intake in Male Competitive Athletes Using the Epic-Norfolk Food Frequency Questionnaire. 2025 Mar 13;15(3):458. doi:10.3390/life15030458
8. Thomas DT, Erdman KA, Burke LM. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and Athletic Performance. J Acad Nutr Diet. 2016 Mar;116(3):501–28. doi:10.1016/j.jand.2015.12.006
9. Michele DE. Mechanisms of skeletal muscle repair and regeneration in health and disease. FEBS J. 2022 Nov 5;289(21):6460–2. doi:10.1111/febs.16577
10. Tidball JG. Mechanisms of Muscle Injury, Repair, and Regeneration. Compr Physiol. 2011 Oct;1(4):2029–62. doi:10.1002/j.2040-4603.2011.tb00387.x
11. Feng L, Li B, Yong SS, Wu X, Tian Z. Exercise and nutrition benefit skeletal muscle: From influence factor and intervention strategy to molecular mechanism. Sports Medicine and Health Science. 2024 Dec;6(4):302–14. doi:10.1016/j.smhs.2024.02.004
12. McGlory C, Devries MC, Phillips SM. Skeletal muscle and resistance exercise

training; the role of protein synthesis in recovery and remodeling. J Appl Physiol. 2017 Mar 1;122(3):541–8. doi:10.1152/japplphysiol.00613.2016

13. Stožer A, Vodopivc P, Križančić Bombek L. Pathophysiology of exercise-induced muscle damage and its structural, functional, metabolic, and clinical consequences. Physiol Res. 2020 Aug 26;565–98. doi:10.33549/physiolres.934371
14. Papanikolaou K, Veskoukis AS, Draganidis D, Baloyiannis I, Deli CK, Poulios A, et al. Redox-dependent regulation of satellite cells following aseptic muscle trauma: Implications for sports performance and nutrition. Free Radic Biol Med. 2020 Dec;161:125–38. doi:10.1016/j.freeradbiomed.2020.10.001
15. Fekete M, Lehoczki A, Kryczyk-Poprawa A, Zábó V, Varga J, Bálint M, et al. Functional Foods in Modern Nutrition Science: Mechanisms, Evidence, and Public Health Implications. Nutrients. 2025 Jun 28;17(13):2153. doi:10.3390/nu17132153
16. Arshad Z, Shahid S, Hasnain A, Yaseen E, Rahimi M. Functional Foods Enriched With Bioactive Compounds: Therapeutic Potential and Technological Innovations. Food Sci Nutr. 2025 Oct 7;13(10). doi:10.1002/fsn3.71024
17. Marone PA, Birkenbach VL, Hayes AW. Newer Approaches to Identify Potential Untoward Effects in Functional Foods. Int J Toxicol. 2016 Mar 9;35(2):186–207. doi:10.1177/1091581815616781
18. Damián MR, Cortes-Perez NG, Quintana ET, Ortiz-Moreno A, Garfias Noguez C, Cruceño-Casarrubias CE, et al. Functional Foods, Nutraceuticals and Probiotics: A Focus on Human Health. Microorganisms. 2022 May 21;10(5):1065. doi:10.3390/microorganisms10051065
19. Fekete M, Lehoczki A, Kryczyk-Poprawa A, Zábó V, Varga J, Bálint M, et al. Functional Foods in Modern Nutrition Science: Mechanisms, Evidence, and Public Health Implications. Nutrients. 2025 Jun 28;17(13):2153. doi:10.3390/nu17132153
20. Grajek W, Olejnik A, Sip A. Probiotics, prebiotics and antioxidants as functional foods ∗ [Internet]. 2004. Report. Available from: www.actabp.pl
21. Fernández-Elías ValentínE, Courel-Ibáñez J, Pérez-López A, Jodra P, Moreno-Pérez V, Coso J Del, et al. Acute Beetroot Juice Supplementation Does Not Improve Match-Play Activity in Professional Tennis Players. Journal of the American Nutrition Association. 2022 Jan 2;41(1):30–7. doi:10.1080/07315724.2020.1835585
22. Guest NS, VanDusseldorp TA, Nelson MT, Grgic J, Schoenfeld BJ, Jenkins NDM, et al. International society of sports nutrition position stand: caffeine and exercise performance. Journal of the International Society of Sports Nutrition. BioMed Central Ltd; 2021. doi:10.1186/s12970-020-00383-4 PubMed PMID: 33388079.
23. Aoi W, Naito Y, Yoshikawa T. Exercise and functional foods. Nutrition Journal. 2006. doi:10.1186/1475-2891-5-15 PubMed PMID: 16749944.
24. Poutanen KS, Kårlund AO, Gómez-Gallego C, Johansson DP, Scheers NM, Marklinder IM, et al. Grains – a major source of sustainable protein for health. Nutr Rev. 2022 May 9;80(6):1648–63. doi:10.1093/nutrit/nuab084
25. Hill JA, Keane KM, Quinlan R, Howatson G. Tart Cherry Supplementation and Recovery From Strenuous Exercise: A Systematic Review and Meta-Analysis. Int J Sport Nutr Exerc Metab. 2021 Mar 1;31(2):154–67. doi:10.1123/ijsnem.2020-0145

26. Vitošević B, Filipović M, Popović L, Sterkowicz-Przybycień K, Purenović-Ivanović T. Juice-Based Supplementation Strategies for Athletic Performance and Recovery: A Systematic Review. Sports. Multidisciplinary Digital Publishing Institute (MDPI); 2025. doi:10.3390/sports13080269
27. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
28. Rickards L, Lynn A, Harrop D, Barker M, Russell M, Ranchordas M. Effect of Polyphenol-Rich Foods, Juices, and Concentrates on Recovery from Exercise Induced Muscle Damage: A Systematic Review and Meta-Analysis. Nutrients. 2021 Aug 27;13(9):2988. doi:10.3390/nu13092988
29. Heaton LE, Davis JK, Rawson ES, Nuccio RP, Witard OC, Stein KW, et al. Selected In-Season Nutritional Strategies to Enhance Recovery for Team Sport Athletes: A Practical Overview. Sports Medicine. Springer International Publishing; 2017. p. 2201–18. doi:10.1007/s40279-017-0759-2 PubMed PMID: 28702900.
30. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
31. Jiao X, Liu X, Cao Q, Deng Z. Plant-based supplements in enhancing exercise performance and recovery. Front Nutr. 2025 Nov 24;12. doi:10.3389/fnut.2025.1699642
32. Kyriakidou Y, Wood C, Ferrier C, Dolci A, Elliott B. The effect of Omega-3 polyunsaturated fatty acid supplementation on exercise-induced muscle damage. J Int Soc Sports Nutr. 2021 Jan 2;18(1). doi:10.1186/s12970-020-00405-1
33. Pearson AG, Hind K, Macnaughton LS. The impact of dietary protein supplementation on recovery from resistance exercise-induced muscle damage: A systematic review with meta-analysis. European Journal of Clinical Nutrition. Springer Nature; 2023. p. 767–83. doi:10.1038/s41430-022-01250-y PubMed PMID: 36513777.
34. Costa MS, Toscano LT, Toscano L de LT, Luna VR, Torres RA, Silva JA, et al. Ergogenic potential of foods for performance and recovery: a new alternative in sports supplementation? A systematic review. Crit Rev Food Sci Nutr. 2022 Feb 16;62(6):1480–501. doi:10.1080/10408398.2020.1844137
35. Li G, Shang L, Wang X, Zhang L, Zhao Y, Ni W, et al. Whey Protein Mitigates Oxidative Stress Injury and Improves Protein Synthesis in Mouse Skeletal Muscle by Regulating the SIRT1/Nrf2/HO-1 Axis and AMPK/TSC2/mTOR/4EBP1 Pathway. J Food Sci. 2025 Jul 14;90(7). doi:10.1111/1750-3841.70286
36. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
37. Li T, Yin D, Shi R. Gut-muscle axis mechanism of exercise prevention of sarcopenia. Front Nutr. 2024 Aug 16;11. doi:10.3389/fnut.2024.1418778
38. Annunziata G, Camajani E, Galasso M, Verde L, Caprio M, Muscogiuri G, et al. Antioxidants and Exercise Performance: Focus on Mediterranean Diet. Antioxidants. 2025 Dec 21;15(1):10. doi:10.3390/antiox15010010
39. Rickards L, Lynn A, Harrop D, Barker M, Russell M, Ranchordas M. Effect of Polyphenol-Rich Foods, Juices, and Concentrates on Recovery from Exercise

Induced Muscle Damage: A Systematic Review and Meta-Analysis. Nutrients. 2021 Aug 27;13(9):2988. doi:10.3390/nu13092988

40. Zhang X, Zhong Y, Rajabi S. Polyphenols and post-exercise muscle damage: a comprehensive review of literature. Eur J Med Res. 2025 Apr 9;30(1). doi:10.1186/s40001-025-02506-6
41. Hill JA, Keane KM, Quinlan R, Howatson G. Tart Cherry Supplementation and Recovery From Strenuous Exercise: A Systematic Review and Meta-Analysis. Int J Sport Nutr Exerc Metab. 2021 Mar 1;31(2):154–67. doi:10.1123/ijsnem.2020-0145
42. Gao R, Chilibeck PD. Effect of Tart Cherry Concentrate on Endurance Exercise Performance: A Meta-analysis. J Am Coll Nutr. 2020 Oct 2;39(7):657–64. doi:10.1080/07315724.2020.1713246
43. Wang L, Meng Q, Su CH. From Food Supplements to Functional Foods: Emerging Perspectives on Post-Exercise Recovery Nutrition. Nutrients. 2024 Nov 27;16(23):4081. doi:10.3390/nu16234081
44. Pearson AG, Hind K, Macnaughton LS. The impact of dietary protein supplementation on recovery from resistance exercise-induced muscle damage: A systematic review with meta-analysis. European Journal of Clinical Nutrition. Springer Nature; 2023. p. 767–83. doi:10.1038/s41430-022-01250-y PubMed PMID: 36513777.
45. Kyriakidou Y, Wood C, Ferrier C, Dolci A, Elliott B. The effect of Omega-3 polyunsaturated fatty acid supplementation on exercise-induced muscle damage. J Int Soc Sports Nutr. 2021 Jan 2;18(1). doi:10.1186/s12970-020-00405-1

HOW TO CITE: Dr Swati Prakash, Shantanu Kumar, Vishakha Jaiswal, Significance of Functional food in Sports nutrition and Muscle recovery, Int. J. of Pharm. Sci., 2026, Vol 4, Issue 4, 3109-3125, https://doi.org/10.5281/zenodo.19661826