Effects of green tea extract on exercise performance and fatigue under different exercise modalities: a scoping review

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Summary. Objective. This study aims to investigate the effects of green tea extract (GTE) on athletic performance and fatigue recovery. The objective is to establish a theoretical foundation for developing strategies to enhance athletic performance. **Methods.** A systematic literature search was conducted using databases including PubMed, Web of Science, and CNKI for relevant research published from 2005 to the present.This article examines the effects of GTE supplementation on athletic performance by synthesizing relevant literature. **Results.** A total of 36 papers were included in this review. The results indicate that supplementation with GTE during regular exercise effectively enhances the activity and expression of endogenous antioxidant enzymes, thereby improving the body's overall antioxidant capacity. Furthermore, GTE supplementation was found to enhance athletic performance. It mitigates oxidative stress induced by high-intensity exercise, which aids in improving physiological function and preventing muscular oxidative damage. Concurrently, it enhances lipid metabolism and fat breakdown during exercise, reduces hepatic glucose consumption, and delays the onset of fatigue. **Conclusions.** Supplementing with GTE during regular exercise effectively enhances the body's antioxidant capacity and improves athletic fitness levels such as endurance. It reduces muscle damage and delays fatigue by mitigating oxidative stress and promoting lipid metabolism.

Effetti dell'estratto di tè verde sulla prestazione atletica e sul recupero dalla fatica

Riassunto. Obiettivo. Il presente studio si propone di indagare gli effetti dell'estratto di tè verde (ETV) sulla prestazione atletica e sul recupero dalla fatica. L'obiettivo è stabilire una base teorica per lo sviluppo di strategie volte al miglioramento delle performance sportive. **Metodi.** È stata condotta una ricerca sistematica della letteratura utilizzando banche dati quali PubMed, Web of Science e CNKI, selezionando ricerche pertinenti pubblicate dal 2005 a oggi. Questo articolo esamina gli effetti della supplementazione di ETV sulla prestazione atletica attraverso la sintesi della letteratura rilevante. **Risultati.** Sono stati inclusi in questa review un totale di 36 articoli. I risultati indicano che l'integrazione con ETV durante l'esercizio regolare migliora efficacemente l'attività e l'espressione degli enzimi antiossidanti endogeni, potenziando così la capacità antiossidante complessiva dell'organismo. Inoltre, è stato riscontrato che la supplementazione di ETV incrementa la prestazione atletica. Essa attenua lo stress ossidativo indotto dall'esercizio ad alta intensità, contribuendo al miglioramento della funzione fisiologica e alla prevenzione del danno ossidativo muscolare. Contemporaneamente, l'ETV incrementa il metabolismo lipidico e la scomposizione dei grassi durante l'esercizio, riduce il consumo epatico di glucosio e ritarda l'insorgenza della fatica. **Conclusioni.** L'integrazione con ETV durante l'esercizio regolare potenzia efficacemente la capacità antiossidante dell'organismo e migliora i livelli di fitness atletica, come la resistenza. Riduce il danno muscolare e ritarda l'affaticamento attenuando lo stress ossidativo e promuovendo il metabolismo lipidico.

Key words. Green tea, competitive fitness, fatigue, antioxidant, exercise performance, oxidative stress, inflammatory response.

Parole chiave. Tè verde, fitness agonistica, fatica, antiossidante, prestazione fisica, stress ossidativo, risposta infiammatoria.

Introduction

Competitive physical fitness represents the highest level of physical conditioning, characterized by adaptation to the demands of competitive sports. As the foundation for athletes to tolerate high-intensity training, the fatigue recovery and physical adaptation processes inherent to competitive physical fitness are vital for sports performance[1]. In competitive settings, high-intensity, overload training is essential for improving performance but can also induce sports injuries. During strenuous exercise, oxidative stress increases, prompting a rapid response from endogenous antioxidant enzymes. An imbalance in this antioxidant redox state can lead to muscle fatigue, inflammatory reactions, and even muscle damage, ultimately impairing athletic performance[2,3]. Muscle fatigue is a significant factor impairing athletic performance. Its underlying mechanisms involve ATP consumption, muscle damage, and an increase in reactive oxygen species (ROS), leading to oxidative stress[4]. During intensive training or competition, athletes' physiological systems must adapt to substantial physical demands to maximize muscular power and maintain optimal competitive capacity[5]. Consequently, achieving peak performance requires athletes to sustain a high level of physical fitness.

The extensive application of emerging technologies in sports training has significantly contributed to the rapid advancement of competitive sports. Research in this field remains a focus domestically and internationally, with the aim of identifying scientific methods to enhance athletic training. Studies indicate that exogenous supplements, including specific dietary components, antioxidants, and pharmaceuticals, are utilized to facilitate physical adaptation and accelerate fatigue recovery in athletes[6-10]. Among these, green tea extract (GTE) supplementation has been shown to effectively manage oxidative stress and mitigate exercise-induced oxidative damage[11,12]. Green tea, which has a long history of consumption as a beverage in China, is rich in polyphenolic compounds such as catechins, flavonols, and flavanols. The primary catechins include epigallocatechin gallate (EGCG), epigallocatechin (EGC), epicatechin gallate (ECG), and epicatechin.Their primary function is to eliminate free radicals and other oxidizing agents while also inhibiting the activity of catalytic enzymes[13]. Among these compounds, EGCG offers the most significant health benefits, particularly for cardiovascular health and metabolism. In sports science, research indicates that green tea and catechins possess strong antioxidant properties that can effectively reduce exercise-induced oxidative damage to cells[14]. Furthermore, green tea extract has been shown to aid in the repair of skeletal muscle injuries in basketball players following high-intensity exercise. It effectively inhibits the breakdown of structural and functional proteins, enhances antioxidant enzyme activity, maintains overall antioxidant capacity, and thereby promotes recovery from fatigue[15].

Relevant studies have confirmed the effects of green tea extract on antioxidative stress, lipid metabolism, and related neuroprotection[16-18]. However, the impact of green tea extract supplementation on athletes' competitive fitness and the mechanisms involved remain unclear. As the modern competitive sporting landscape intensifies, athletes require superior fitness levels to excel in high-intensity competition. Therefore, by reviewing extant literature on green tea extract, this review aims to explore its effects on post-exercise physical adaptation and fatigue recovery, and to evaluate its potential for enhancing competitive fitness. The findings are intended to provide theoretical guidance and practical value for scientific sports training.

Data and methods

Design

A scoping review represents a form of knowledge synthesis that systematically maps the existing literature by searching, selecting, and synthesizing available evidence. It serves to outline key concepts within a field, identify research trends, characterize the diversity of existing knowledge, and inform future research directions[19].This study strictly adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines as outlined by Tricco et al[20].

Data sources

A systematic search was conducted using the databases PubMed, Web of Science, China National Knowledge Infrastructure (CNKI), and Dimensions to identify relevant research articles published between 2005 to present. The search strategy employed keywords including green tea,competitive fitness,fatigue,antioxidant,exercise performance, oxidative stress, and inflammatory response.

Inclusion criteria

1. The research focuses on athletes participating in various sports events supplemented with green tea extract.
2. The experimental group has a strict exercise prescription design.
3. The supplement for the experimental group must be green tea extract, while the control group can

be supplemented with other nutrients or without intervention
4. The prescription design follows the standards of the American School of Sports Medicine (ACSM). The evaluation indexes mainly include competitive fitness,fatigue,antioxidant,exercise performance, oxidative stress.

Exclusion criteria

1. Excluding non-English or non-Chinese literature.
2. Exclude repetitive and nonexperimental studies.
3. Excluding and supplementing literature unrelated to green tea extracts and competitive fitness.

Data intake quality assessment

1. The shortlisted literature is read in three stages. In the first stage, researchers search the database, browse titles and abstracts, and preliminarily screen the literature they have retrieved; In the second stage, another researcher sorted out the literature and excluded duplicate ones; In the third stage, two researchers read all the literature to determine whether it meets the inclusion criteria. If there is no consensus on any literature, it will be decided whether to include it after discussion.

Results

Bibliographic overview

The system search results are shown in figure 1. A total of 1231 relevant articles were retrieved from four databases. Deleted 340 duplicate literature, and selected 891 kinds of literature According to the title and abstract, 121 full texts were obtained for further analysis, of which 85 were excluded because they did not meet the qualification criteria. Through the full-text analysis, 36 papers meet the qualification criteria. The number of articles finally included in this paper is 36.

Exercise and antioxidant capacity

High-intensity, heavy-load exercise generates substantial quantities of ROS and reactive nitrogen radicals. When ROS levels surpass the scavenging capacity of the body's antioxidant system, the condition progresses from elevated ROS to oxidative stress, creating an imbalance in the redox state[21,22]. Although oxidative stress is a physiological response, chronic

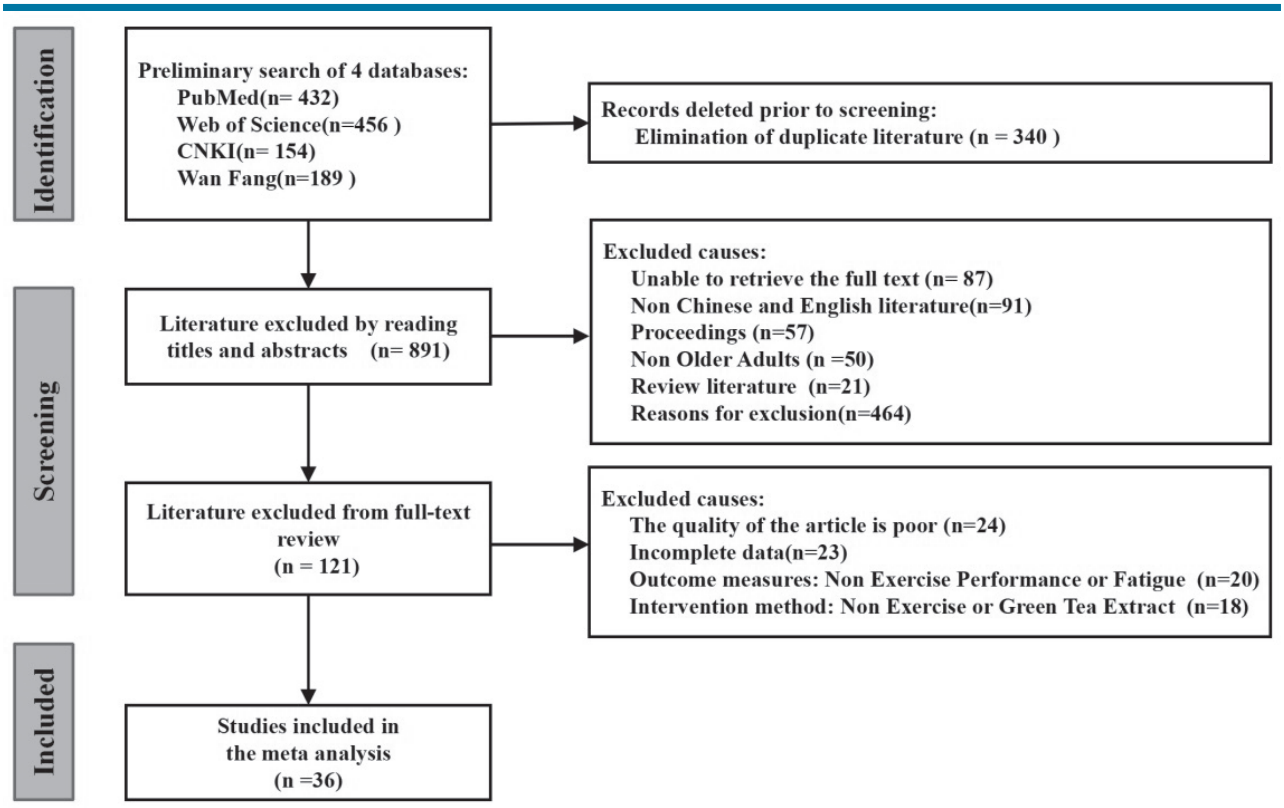

Figure 1. Literature retrieval and screening process.

oxidative stress is strongly associated with the incidence of various diseases, including diabetes, cardiovascular conditions, and nervous system disorders, as well as accelerated aging[21-24]. Consequently, maintaining redox balance is crucial for human health. It is important to note that normal skeletal muscle function requires a basal physiological level of ROS. Conversely, excessively high ROS levels impair muscle contraction, leading to weakness and fatigue[25]. Competitive exercise can elevate ROS production, leading to oxidative damage of lipids, proteins, and DNA. This damage contributes to muscle fatigue and impaired exercise performance. The extent of exercise-induced oxidative stress is primarily determined by the exercise type, intensity, training status of the individual, and endogenous antioxidant capacity[26]. To mitigate this damage, the body employs an intrinsic antioxidant defense system comprising enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH Px). Additionally, exogenous non-enzymatic antioxidants, including vitamin C, vitamin E, and bilirubin, provide further antioxidant support[24,25]. These antioxidants effectively inhibit the oxidation of biological molecules, both inside and outside cells. As the primary defense against superoxide free radicals, SOD catalyzes their dismutation into less reactive hydrogen peroxide and oxygen[27]. Subsequently, CAT and GSH-Px further decompose hydrogen peroxide into water and oxygen, completing the detoxification process. The body's antioxidant system thus comprises endogenous antioxidants and exogenous antioxidant supplements[28], and the balance between this antioxidant capacity and oxidative stress levels is critical. Consequently, enhancing endogenous antioxidant levels may improve the body's ability to tolerate intense exercise and enhance athletic performance[27]. Research indicates that the endogenous antioxidant system in skeletal muscle exhibits considerable plasticity. Aerobic exercise enhances the function of this system by upregulating the expression of antioxidant enzymes, thereby mitigating exercise-induced oxidative stress[26]. Endurance exercise, in particular, improves skeletal muscle's adaptive capacity to training[29] and induces the upregulation of various endogenous antioxidant enzymes[30]. This adaptation is evidenced by increased activity levels of SOD and glutathione peroxidase in serum[25,31]. Supporting this, animal studies demonstrate that endurance training significantly elevates serum SOD activity in mice, which serves to protect cellular structures from damage caused by high-level oxidative stress[32].

In conclusion, although regular endurance training enhances the body's antioxidant capacity, the associated exercise-induced oxidative stress can overwhelm endogenous antioxidant defenses[33]. When the production of ROS and other superoxides during strenuous exercise exceeds the body's scavenging capacity, oxidative damage to cells becomes inevitable, leading to muscle cell impairment and reduced performance. Therefore, supplementing with exogenous antioxidants is necessary to maintain oxidative balance and mitigate such damage.

Effects of adding green tea extract on different exercise modes

Athletic performance is closely linked to the body's capacity for high-intensity exertion and muscular power. Mitigating oxidative damage during intensive competition is crucial for maintaining optimal performance. Furthermore, different sports and exercise intensities impose distinct physiological demands, necessitating specific physical adaptations. For instance, endurance sports require superior stamina and a sustained energy supply. Therefore, investigating and leveraging the ergogenic benefits of green tea extract across various disciplines is essential for comprehensively enhancing athletes' competitive fitness.

The effect of supplementing green tea on resistance movement

The administration of GTE before and after resistance exercise training exerts dose-dependent effects on vascular function. Research indicates that high-dose GTE enhances local blood flow following resistance exercise[34], thereby improving the delivery of nutrients and oxygen to meet increased metabolic demands. This finding is supported by a study involving elderly subjects, where acute GTE supplementation significantly increased microvascular perfusion and promoted muscle perfusion[35]. Beyond its vascular benefits, GTE supplementation may also mitigate exercise-induced oxidative damage. In a study of 14 healthy men who consumed green tea three times daily (2 g per serving) alongside four sets of bench press training, supplementation was found to inhibit the elevated expression of creatine kinase and xanthine oxidase[36]. Research on the effects of green tea extract supplementation reveals potential benefits for mitigating exercise-induced oxidative stress. One study involving obese men undergoing resistance exercise found that 14-day supplementation did not alter lipid peroxidation but significantly improved the overall oxidative stress state and protected against exercise-induced DNA oxidative damage [37]. Similarly, a four-week intervention combining green tea intake with strength and endurance training enhanced resting plasma antioxidant potential, provided muscle protection, and prevented oxidative damage from both short-term endurance and long-term strength training[38]. In contrast, other evidence indicates that acute, single-dose epicatechin supplementation has a

minimal effect on human vasodilation[39]. Collectively, these findings suggest that epicatechin possesses the potential to enhance vascular function and reduce oxidative stress to improve exercise performance; however, this effect is likely dependent on specific dosage strategies and exercise prescriptions.

Supplement green tea extract and aerobic exercise

Aerobic exercise enhances physical adaptation, in part, by improving the capacity of the antioxidant defense system. Supporting this, Jówko et al. demonstrated that a four-week supplementation with 980 mg of catechin increased post-exercise total antioxidant activity and superoxide dismutase activity in runners[40]. Although this intervention had a minimal effect on muscle injury markers, it enhanced overall antioxidant capacity. Exercise under conditions of environmental heat stress is known to increase the risk of heat-related illnesses, as it exacerbates exercise-induced inflammatory responses and oxidative stress. In such scenarios, green tea supplementation may be an effective strategy for mitigating high temperature-related complications[15]. Research indicates that consuming green tea 90 minutes prior to exercise can attenuate the rise in TNF-α. Furthermore, the lipid antioxidant properties of green tea can improve athletes' overall antioxidant status, thereby potentially reducing muscle damage and enhancing athletic performance [41].Research on elite footballers suggests that the concurrent intervention of aerobic exercise and green tea intake can repair and inhibit skeletal muscle injury, remove excessive free radicals and metabolites, and accelerate fatigue recovery[42,43]. Supporting this, a study of 24 rowers randomly assigned to placebo and green tea extract groups found that levels of GSH Px, SOD, and CAT were significantly higher in the supplement group, leading to the conclusion that green tea extract enhances both overall antioxidant capacity and aerobic exercise capacity[44]. However, contrasting evidence indicates that while six weeks of green tea supplementation improves antioxidant status and significantly reduces malondialdehyde (MDA), it does not affect markers of muscle injury[45]. A recent review further suggests a linear negative correlation between the dosage of green tea supplementation and changes in MDA, proposing that such supplementation boosts antioxidant capacity and may mitigate the risk of chronic diseases associated with oxidative stress[46]. Finally, a study on green tea combined with comprehensive fitness training found that six weeks of green tea extract supplementation had minimal effect on aerobic capacity or serum BDNF levels in men, but it significantly improved blood antioxidant capacity and moderately reduced lipid peroxidation and oxidative damage induced by training[47].

Supplement green tea extract and endurance exercise

Research indicates that improving fat utilization and antioxidant capacity can enhance performance in endurance sports[47]. Supporting this, one study found that daily green tea intake during endurance training not only preserved the adaptive benefits of training but also enhanced overall antioxidant capacity[48]. Furthermore, in a study on a cycling endurance group supplemented with green tea, the combination was found to reduce acute exercise-induced CK release, alleviate delayed onset muscle soreness, and increase the proportion of fat utilized during exercise, thereby enhancing endurance performance[49]. The ergogenic effect of green tea supplementation is also well-documented in animal studies. For instance, mice fed green tea extract exhibited a significant decrease in plasma lactic acid concentration and an increase in plasma free fatty acids after endurance exercise, indicating an enhanced rate of fat utilization[50]. EGCG, a primary catechin in green tea, has been shown to enhance human endurance. This indicates that the endurance-improving effects of green tea extract are mediated by its catechins[51]. Furthermore, green tea extract appears to improve endurance not only by increasing the metabolic capacity of skeletal muscle but also by promoting the utilization of fatty acids as an energy source[51]. Research also suggests that long-term catechin intake can mitigate exercise-induced muscle damage; by enhancing antioxidant properties, it reduces muscle injury from strenuous activities like downhill running and accelerates recovery in mice by suppressing inflammatory response and oxidative stress[43]. In mouse swimming models, green tea extract has been demonstrated to enhance endurance by acting on slow-twitch muscle fibers, increasing the expression of genes responsible for Ca2+ balance regulation, and improving the adaptability of these fibers[52]. Despite substantial evidence from human and animal studies supporting the ergogenic benefits of green tea, some early research presents divergent results. For instance, low-dose supplementation was found to have no significant effect on athletes' endurance training and energy metabolism[53], and acute supplementation of green tea polyphenols did not influence oxidative stress or muscle damage[43]. These contrasting findings suggest that the effects of green tea supplementation on training adaptation are variable and likely depend on factors such as dosage and duration of intake.

In summary, interventions involving GTE supplementation to enhance athletic performance have garnered increasing attention. The data reviewed in this paper indicate that GTE supplementation positively influences sports performance and improves competitive fitness without apparent side effects, which is consistent with previous research[54,55]. Although GTE supplementation enhances fitness levels and

performance markers, it is important to note that its benefits vary across different exercise modalities. In resistance exercise, the positive effects may be attributable to improvements in vascular function. In aerobic exercise, GTE supplementation appears to reduce oxidative stress, increase maximal oxygen uptake, and enhance aerobic capacity. The most pronounced benefits are observed in endurance sports, potentially due to the high energy demands of such activities. This review has discussed the effects of GTE on resistance, aerobic, and endurance exercise; however, its impact on other modalities, such as anaerobic and coordinative exercise, remains unknown due to a current lack of research. Future studies should investigate the effects of different dosages and cycles of GTE intake on performance across a wider range of exercise modes.

Effect of adding green tea extract on the fatigue

Fatigue induced by competitive sports is a complex phenomenon encompassing psychological disturbances, central nervous system dysfunction, mechanical fatigue, and impaired muscle contraction[56,57]. When the body fails to recover adequately during or after sustained high-intensity exercise, this fatigued state compromises muscle strength and power, leading to diminished athletic performance[3]. Consequently, effective management of sports-induced fatigue is essential for maintaining high fitness levels and enabling athletes to achieve optimal performance. From a physiological perspective, the potential role of green tea supplementation in alleviating fatigue can be examined through its influences on oxidative stress, energy metabolism, and inflammatory pathways, thereby improving overall fitness in competitive sports.

Supplement of green tea extract and oxidative stress

Since the discovery of exercise-induced oxidative stress, evidence has confirmed its role as a significant contributor to exercise fatigue, leading to reduced muscle strength and atrophy[4,58]. In athletes, this state can easily lead to inadvertent overtraining[24]. Research indicates that supplementation with GTE can effectively mitigate oxidative stress. Pre-exercise GTE administration has been shown to reduce exercise-induced inflammatory and oxidative stress markers, while also improving athletes' maximal oxygen uptake and enhancing aerobic capacity[42]. In a study involving 18 Taekwondo athletes and 22 wrestlers randomly assigned to anaerobic exercise combined with GTE supplementation, the results demonstrated that GTE effectively increased serum CK and urea enzyme activities in wrestlers under high-intensity anaerobic conditions. Furthermore, it promoted the activity of glutathione peroxidase in Taekwondo athletes [59]. These findings suggest that GTE supplementation enhances antioxidant enzyme activity, accelerates the clearance of oxygen free radicals and metabolites, reduces the breakdown of functional and structural proteins induced by anaerobic exercise, and facilitates the repair of oxidative stress-mediated muscle damage[59]. Supporting this, Zhang Shujun noted that GTE not only counteracts oxidative stress but also enhances serum activity in athletes, thereby alleviating muscle strain[60]. Although green tea supplementation has been shown to mitigate exercise-induced muscle damage and oxidative stress, it does not appear to alleviate the sensation of delayed-onset muscle soreness[61]. During high-intensity exercise, increased oxygen consumption can induce oxidative stress, contributing to muscle fatigue. In a study by Hadi et al., 18 football players supplemented with green tea extract for six weeks exhibited a significant reduction in MDA levels and a marked increase in total antioxidant capacity[45]. This indicates that green tea improved the players' oxidative stress status; however, the intervention did not reduce markers of muscle injury. Similarly, a four-week supplementation with 980 mg of tea catechins daily in sprinters led to increased activities of erythrocyte SOD and glutathione peroxidase, alongside improved total antioxidant capacity, MDA, and CK levels. These findings suggest that green tea effectively prevents oxidative stress from repetitive high-intensity exercise. Notably, however, the outcome indices also concluded that green tea extract supplementation could not prevent exercise-induced muscle injury[42].

Research has demonstrated that green tea extract supplementation can alleviate oxidative stress; however, its effect on the state of muscle injury remains unclear. A recent study involving 28 amateur athletes found that green tea supplementation resulted in a lower response degree of muscle injury and oxidative stress to fatigue. Furthermore, exercise-induced excessive fatigue can lead to a decline in neuromuscular function and impaired training adaptation, which may cause impaired performance during continuous exercise in competition. Notably, green tea extract supplementation has been shown to ameliorate neuromuscular function in individuals with chronic fatigue[5]. In a separate in vitro study, Cai et al. observed the neuroprotective effect of green tea against oxidative stress in PC12 cells, suggesting that green tea may be an effective strategy for restoring muscle function during sustained exercise[62.] Regarding dosage, Rojano Ortega suggests that acute supplementation with green tea extract has a minimal effect on overall antioxidant capacity and oxidative stress. In contrast, supplementation for more than one week, both before and after exercise, may effectively enhance antioxidant capacity and protect cells from oxidative stress[11].

Supplement green tea extract and energy metabolism

As the primary energy substrates for exercise, carbohydrates and fats are oxidized to meet metabolic demands. The body's storage of fat is substantially greater than that of glycogen. During prolonged, low-intensity exercise, a significant amount of intramuscular fat is oxidized, while carbohydrate utilization remains relatively low. Conversely, as exercise intensity increases, the proportion of energy derived from carbohydrates rises, whereas the contribution from fat decreases[63]. Although regular training enhances fat utilization efficiency and optimizes glycogen allocation during exercise, thereby effectively delaying the onset of fatigue, excessive exercise can induce oxidative stress and DNA damage. These effects may lead to physiological dysfunction and impair athletic performance[64]. Therefore, enhancing lipid metabolism represents a potential strategy for improving athletes' fitness levels.

Studies indicate that medium- to long-term endurance exercise, when combined with green tea supplementation, enhances fat oxidation. In the study by Venables et al.[65], 12 healthy men consumed a green tea extract capsule and performed 30 minutes of cycling at 60% V˙O2max. This acute intake significantly increased the contribution of fat oxidation to total energy expenditure, suggesting it can improve fat oxidation during moderate-intensity exercise, as well as insulin sensitivity and glucose tolerance. Furthermore, compared to endurance training alone, green tea supplementation combined with training improved interleukin-6 and serum adiponectin concentrations, indicating anti-inflammatory and fat metabolism benefits, along with enhanced endurance performance[66,67]. In a related study, twelve women ingested three green tea extract capsules the day before an intermittent sprint test and one capsule 90 minutes prior. Analysis via indirect calorimetry showed that short-term green tea consumption significantly increased fat oxidation and plasma glycerol levels both before and after the sprint. Notably, while adrenaline levels rose during exercise, norepinephrine levels were elevated after exercise following green tea intake[68]. A four-week intervention combining green tea supplementation with exercise altered the subjects' relative fat content and body composition. This suggests that EGCG intake may regulate cellular signaling pathways to enhance fat utilization and improve energy output during exercise[69]. In a related context, recent research indicates that green tea supplementation accelerates local blood flow following resistance exercise, thereby promoting nutrient transport and metabolite clearance[35]. Earlier reviews have associated long-term green tea intake with changes in fat metabolism gene expression, such as the upregulation of fat-metabolizing enzyme genes in skeletal muscle and the downregulation of lipogenic genes in the liver[48]. Sugita et al. propose that a single dose of green tea can influence oxidative stress biomarkers via the catechol-O-methyltransferase mechanism, which favors oxidative metabolism during both rest and exercise[70]. Supporting evidence from animal studies includes an experiment where green tea extract gavaged at low, medium, and high doses to male rats improved intramuscular fatty acid synthesis and regulated lipid metabolism to supply energy for exercise[71]. Similarly, exercised mice fed catechins exhibited a significant decrease in plasma lactic acid concentration and an increase in plasma free fatty acids, indicating a shift towards greater fat utilization as an energy source[49]. Finally, the combination of exercise and EGCG intervention in rats effectively improved blood lipid metabolism and hepatic lipase activity, thereby promoting fat oxidation[72]. Research indicates that green tea supplementation accelerates energy consumption to varying degrees, particularly the oxidation of fat as a primary energy substrate. Regarding the potential impact on skeletal muscle glycogen synthesis, Tsai et al.[73] found that an 8-week supplementation of green tea extract increased whole-body fat oxidation in cyclists to meet the demands of endurance exercise but did not appear to affect muscle glycogen synthesis. However, the effect of green tea on energy metabolism is inconsistent across studies. For instance, Eichenberger et al.[54] reported that green tea extract supplementation had minimal effect on fat and energy metabolism during cycling training. Another study simulating the upper-body exercise of rowers found that green tea supplementation did not increase fat oxidation in the upper limbs, suggesting women performing such exercise are unlikely to benefit from supplementation[74]. Similarly, research on the duration of green tea extract intake concluded that it did not alter whole-body fat oxidation rates or blood metabolites related to fat metabolism during moderate-intensity exercise[75]. These discrepancies are likely attributable to differences in experimental subjects, leading to varied physiological responses. Furthermore, the effects of green tea extract on energy metabolism may differ based on exercise intensity, type, and duration.

Previous studies have yielded inconsistent findings regarding the efficacy of green tea supplementation in ameliorating individual inflammatory responses. Furthermore, the hypothesis that it promotes recovery from fatigue by inhibiting exercise-induced inflammation lacks consistent support. For instance, Eichenberger et al. reported that a 3-week supplementation period did not alter interleukin-6 (IL-6) concentration following submaximal intensity exercise, nor did it significantly enhance exercise performance [53]. Similar studies indicate that, aside from a minor effect on C-reactive protein, green tea extract supplementation has no impact on cyclists'

time-trial performance or energy metabolism. In a study by Suzuki K, nine well-trained male cyclists completed three sessions of eight repeated 100-meter uphill sprints. Although they ingested green tea with carbohydrates during recovery, the supplementation did not improve inflammatory marker levels or cycling performance. However, a recent study found that consuming green tea extract 90 minutes before exercising in high temperatures attenuated the rise in tumor necrosis factor-alpha (TNF-α) and reduced the inflammatory response[76].

Animal studies have investigated the effects of green tea extract supplementation on inflammatory factors and oxidative stress in mice subjected to a 3-week downhill running protocol. The findings indicate that catechin intake maintained mouse endurance and increased oxygenase activity in the gastrocnemius muscle by 22%. Notably, levels of TNF-α, interleukin-1β (IL-1β), and monocyte chemoattractant protein-1 (MCP-1) in the gastrocnemius muscle were significantly reduced by 33%, 29%, and 35%, respectively[77]. As downhill running is a form of eccentric exercise known to induce muscle damage, these results suggest that green tea extract supplementation can alleviate the associated fatigue and inflammatory response. Supporting this, other studies have confirmed that catechin reduces inflammation and muscle strength loss induced by eccentric exercise. For instance, 8-week catechin supplementation significantly attenuated the decline in muscle strength and the increase in inflammatory mediators in plasma and gastrocnemius muscle following downhill running[78]. In a related study, Liu et al.[79] randomly assigned 24 rats to one of three groups: a sedentary control group, an exhaustive swimming group, and an exhaustive swimming group supplemented with green tea. The researchers observed the effects on fatigue indices after a single bout of exhaustive swimming. The green tea intervention group demonstrated significantly improved exercise performance compared to the other groups. Furthermore, supplementation with green tea extract reduced serum levels of TNF-α, IL-1β, IL-6, CK, and lactate dehydrogenase (LDH). Additionally, the ratio of IL-10 to TNF-α in serum was significantly increased.

Substantial evidence supports the efficacy of green tea extract in alleviating fatigue through distinct mechanisms: oxidative stress reduction, energy metabolism modulation, and inflammatory response. First, green tea supplementation enhances the endogenous antioxidant system, boosting overall antioxidant levels to facilitate recovery and protect against exercise-induced muscle damage, as documented[16]. Second, it acts as a metabolic modulator by promoting fat oxidation, which spares glycogen, delays fatigue, and extends endurance during prolonged exercise. Finally, limited human trial data suggest that green tea extract has minimal impact on exercise-induced inflammatory markers across different exercise modalities. Future research should specifically investigate its effects under high-intensity exercise conditions.

Conclusions and future perspectives

Supplementing with green tea extract during regular exercise effectively enhances the body's antioxidant capacity and improves athletic fitness levels such as endurance. It reduces muscle damage and delays fatigue by mitigating oxidative stress and promoting lipid metabolism.

The performance-enhancing effects of GTE are influenced by multiple factors including dosage, supplementation cycles, exercise patterns, and individual training status. Future research should integrate sport-specific requirements to optimise supplementation protocols, with a focus on elucidating its mechanisms of action and key signalling pathways across diverse physiological conditions.

Conflicts of interest. The authors declare that there is no conflict of interest.

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