Review

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Review

The Impact of Physical Exercise on Oxidative and Nitrosative Stress: Balancing the Benefits and Risks

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Abstract: This general review assesses the impact of physical exercise on oxidative and nitrosative stress and the counteractive role of antioxidants, drawing from a systematic literature search up to March 2024 in databases like PubMed and Web of Science. The review highlights studies on the effect of exercise on the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) and antioxidant responses in both human and animal models based on rigorous inclusion and exclusion criteria. Due to the variety of exercise types and participants' characteristics, a narrative synthesis approach was adopted. The findings indicate that moderate exercise boosts antioxidant defenses, known as hormesis, whereas excessive physical activity may increase oxidative and nitrosative damage. The review also explores the complex effects of antioxidant supplementation, revealing that while natural dietary antioxidants support health, high-dose supplements could potentially hinder positive adaptations to exercise. Recommendations for athletes and the general active population highlight the importance of balancing exercise and dietary intake to optimize health benefits. The review concludes with a call for more detailed research on tailored exercise and nutrition plans to dissect these intricate relationships further.

Keywords: exercise physiology; oxidative stress; antioxidant mechanisms; hormesis; nutritional antioxidants; exercise recovery; inflammation response

1. Introduction

Frequent physical activity is closely linked to the body's ability to regulate oxidative and nitrosative stress, which involves producing and accumulating reactive oxygen species (ROS) and reactive nitrogen species (RNS). These biochemical processes are vital for cellular signaling, regulation, and balance [1,2]. The effects of exercise-induced oxidative stress on the body can be positive or negative, depending on factors like exercise intensity, duration, and personal health status [3,4]. Regular exercise has been shown to enhance the body's antioxidant capacity and redox balance, resulting in various health benefits. However, excessive or inappropriate exercise can lead to increased oxidative damage and impairments in muscle function. The connection between exercise and oxidative stress is intricate and influenced by the specific exercise type, intensity, and duration. In certain circumstances, such as high oxidative stress or insufficient dietary antioxidant intake, antioxidant supplementation may be advantageous. Further research is necessary to fully comprehend the impact of various exercise protocols on oxidative and nitrosative stress management in different populations.

1.1. Importance of Understanding Oxidative and Nitrosative Stress

The role of oxidative and nitrosative stress in the development of diseases such as cardiovascular diseases, neurodegenerative disorders, diabetes, and cancer cannot be overstated. These stresses have

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a dual nature, with the potential to be damaging at high levels and regulatory at low levels. Reactive oxygen species (ROS) and reactive nitrogen species (RNS) can impact health and disease in complex ways, modulating inflammation, apoptosis, and mitochondrial function. High levels of ROS resulting from oxidative stress have been linked to the pathology of many diseases, including metabolic syndrome, atherosclerosis, Alzheimer's disease, and rheumatoid arthritis [5]. Oxidative stress is also related to various chronic diseases, such as cardiovascular diseases, neurodegenerative diseases, infections, and cancer [6]. Excessive ROS production can alter cellular structure and function, leading to aging and chronic degenerative pathologies [7]. However, antioxidant interventions can help mitigate oxidative stress and its effects on cardiovascular health [8]. Antioxidants have been shown to reduce the harmful effects of oxidative stress on the body, helping to promote better health and reduce the risk of disease [9].

1.2. Brief Overview of Mechanisms Behind Exercise-Induced Stress Responses

Participation in physical exercise can augment metabolism by producing reactive oxygen species (ROS) and reactive nitrogen species (RNS). During aerobic activities, muscles consume more oxygen, leading to electron leakage from the mitochondrial electron transport chain and an escalation in ROS [10]. Although this increase in ROS and RNS may threaten cellular integrity, it also acts as a crucial signal for activating antioxidant defenses and other protective mechanisms [11]. However, if oxidation products surpass the antioxidant defense capability, the body experiences oxidative stress, significantly affecting muscles' molecular, structural, and functional integrity [12]. Fortunately, regular physical exercise can stimulate the erythroid-related nuclear factor 2 (NRF2) and the antioxidant-responsive-elements (ARE) signaling pathway, which can enhance cellular antioxidant defenses and maintain cellular homeostasis and proper mitochondrial function [13].

Engaging in routine physical activity triggers the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) in the skeletal muscle, resulting in cellular adaptations. These adaptations include an uptick in the production of endogenous antioxidant enzymes, which boost the muscle's capacity to eliminate ROS and RNS. This, in turn, contributes to the numerous health advantages connected with regular physical activity, such as better cardiovascular health, heightened insulin sensitivity, and improved muscle function [14,15].

When we exercise, our bodies naturally produce nitric oxide (NO) through endothelial nitric oxide synthase (eNOS). Nitric oxide is crucial in widening blood vessels, regulating blood flow, and delivering nutrients to our active muscles. However, excessive amounts of NO can combine with superoxide to create a potent oxidant known as peroxynitrite. This peroxynitrite can cause nitrosative stress, which can harm our health. As a result, it is essential to balance the benefits and potential risks of exercise-induced stress [16–18].

2. Methodology

2.1. Criteria for Literature Selection

This review concentrated on empirical research, including quantitative and qualitative studies, to examine the effects of physical exercise on oxidative and nitrosative stress. We also included systematic reviews and meta-analyses to provide a comprehensive perspective, covering literature published in the last 20 years to reflect recent trends and findings. The search was limited to articles in English due to language proficiency constraints, recognizing that this may exclude relevant studies in other languages.

2.2. Search Strategy Description

A thorough literature search was conducted across several databases, including PubMed, Web of Science, Scopus, and Google Scholar, using keywords related to "physical exercise" and oxidative and nitrosative stress markers. Boolean operators were used to refine the search. The approach aimed to synthesize insights from various studies through narrative synthesis, focusing on thematic analysis to identify key themes, comparative analysis to note differences and similarities across studies, and

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evidence integration to construct a cohesive narrative on the impacts of physical exercise on oxidative and nitrosative stress levels.

3. Exercise-Induced Oxidative Stress

3.1. Sources of Free Radicals during Exercise

During exercise, the body's metabolic rate escalates, significantly increasing oxygen consumption and producing reactive oxygen species (ROS), heightening oxidative stress potential [19]. Mitochondria, crucial for ATP production, become primary sources of ROS as their electron transport chain leaks electrons during heightened activity, potentially causing oxidative damage. However, exercise can induce protective mechanisms, such as the superassembly of mitochondrial complex I in rats, reducing lipid peroxidation and mitochondrial oxidative damage, suggesting therapeutic benefits for metabolic diseases [20,21]. Ischemia-reperfusion injury, resulting from temporary blood flow restriction followed by reoxygenation in muscle tissues, also contributes to ROS generation, underscoring the role of oxidative stress in exercise-induced muscle damage and the potential mitigating effects of antioxidant supplementation [22]. The body's inflammatory response to exercise activates immune cells like neutrophils and macrophages, producing free radicals crucial for muscle repair and regeneration, with inflammation playing a vital role in recovery [23]. Additionally, catecholamines such as adrenaline can autoxidize, forming free radicals; however, enzymatic reactions and metal ions are more likely sources at physiological pH, with the potential for oxidative damage in cardiac cells [24]. Despite the risks of excessive free radical production, moderate levels can prompt adaptive responses that benefit health, emphasizing the importance of understanding these mechanisms to optimize antioxidant defenses and muscle health [25]. Regular physical activity enhances the body’s antioxidant capacity, protecting against oxidative stress and underscoring the adaptive complexity of exercise-induced oxidative stress [26].

3.2. Antioxidant Responses to Acute and Chronic Exercise Conditions

The body defends against exercise-induced oxidative stress through enzymatic antioxidants like superoxide dismutase, catalase, and glutathione peroxidase, and non-enzymatic antioxidants such as vitamins C and E, enhancing its ability to neutralize reactive oxygen species (ROS). Acute exercise transiently boosts these antioxidants, providing immediate protection. In contrast, chronic exercise leads to genetic adaptations that increase the body's antioxidant capacity over time, demonstrating the hormesis effect where moderate oxidative stress stimulates more robust defenses [19]. Computational studies show antioxidants can influence enzyme structures, aiding disease prevention [27]. The production of ROS during exercise, through mechanisms like mitochondrial activity and inflammation, is crucial for muscle adaptation, including angiogenesis and hypertrophy, influenced by exercise type and intensity [28]. Balancing antioxidant intake with training is essential for athletes to optimize performance and recovery, highlighting the complex interplay between ROS, antioxidants, and exercise [29]. Table 1 in our study briefly overviews the exercise-induced oxidative stress mechanisms and antioxidant responses.

Table 1. Detailed Overview of Exercise-Induced Oxidative Stress Mechanisms and Antioxidant Responses.

Category	Details	References
Metabolic Rate & Oxygen Consumption	Increased metabolic rate during exercise leads to higher oxygen consumption and production of ROS, posing a potential for oxidative damage.	[19,26]
Sources of ROS	Primary sources of ROS include mitochondria, ischemia-reperfusion injury, inflammation, and catecholamines (such as adrenaline).	[20–24]

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Protective Mechanisms & Adaptations	Exercise induces protective mechanisms reducing lipid peroxidation and oxidative damage, and regular activity enhances the body's antioxidant capacity.	[25,26]
Enzymatic Antioxidants	The body utilizes enzymatic antioxidants like superoxide dismutase, catalase, and glutathione peroxidase against oxidative stress.	[19]
Non-Enzymatic Antioxidants	Non-enzymatic antioxidants include vitamins C and E, which enhance the body's ability to neutralize ROS.	[19]
Adaptive Responses to Exercise	Acute exercise transiently boosts antioxidants, providing immediate protection. Regular exercise leads to genetic adaptations that increase the body's antioxidant capacity, demonstrating the hormesis effect.	[19,27–29]

4. Exercise-Induced Nitrosative Stress

4.1. Exploration of the Role of Nitric Oxide in Exercise Physiology

Nitric oxide (NO) enhances blood flow, oxygen delivery, and muscle nutrient supply during exercise, improving performance and endurance. Its production increases with physical activity, mediated by enzymes like endothelial and neuronal nitric oxide synthase (eNOS and nNOS), promoting vasodilation and muscular perfusion. Aging reduces NO bioavailability, affecting exercise capacity. However, regular aerobic exercise and dietary strategies to boost NO, such as inorganic nitrate, nitrite, l-arginine, and l-citrulline supplements, can mitigate these effects, particularly in older adults [30,31]. Furthermore, exercise-induced NO release improves vascular function and cardiovascular health, even in patients with vascular diseases. NO also enhances mitochondrial biogenesis and efficiency, which is crucial for increasing endurance and reducing fatigue in prolonged activities [32]. Regular physical activity, therefore, not only helps maintain NO levels in aging but also leverages its benefits for cardiovascular and muscular health.

4.2. Examination of the Consequences of Excessive Nitrosative Stress Due to Physical Activity

While moderate nitric oxide (NO) levels benefit health and exercise adaptation, excessive NO can cause nitrosative stress, leading to cellular damage. High NO levels react with superoxide anions to form peroxynitrite, a potent oxidant that can damage lipids, DNA, and proteins, altering cell function and integrity. Such stress is linked to various diseases, including cardiovascular and neurodegenerative disorders and inflammation. Too much NO can impair recovery, increase muscle fatigue, and reduce performance in exercise. The body has mechanisms, like protein nitrosation and denitrosylation, to regulate NO effects; however, an imbalance in these processes can lead to health issues, significantly affecting the central nervous system [33,34]. Additionally, the body produces reactive oxygen species (ROS) in different locations, including the mitochondria and endoplasmic reticulum, impacting cellular activities and contributing to pathological conditions when mismanaged. Understanding how to control NO and ROS levels is crucial for preventing oxidative and nitrosative stress-related diseases, emphasizing the importance of maintaining a balance to support cellular function and health [35]. For comprehensive information on exercise-induced nitrosative stress: mechanisms, benefits, and regulatory strategies, refer to Table 2.

Table 2. Detailed Insights into Exercise-Induced Nitrosative Stress: Mechanisms, Benefits, and Regulatory Strategies.

Category	Details	References
Role of Nitric Oxide (NO)	NO enhances blood flow, oxygen delivery, and muscle nutrient supply during exercise, improving performance and endurance.	[32]

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Enzymes Mediating NO Production	NO production is increased with physical activity, mediated by enzymes like endothelial and neuronal nitric oxide synthase (eNOS and nNOS).	[30,31]
Benefits of NO in Exercise	Regular aerobic exercise and dietary strategies that boost NO can improve vascular function and mitochondrial efficiency, benefiting cardiovascular and muscular health.	[32]
Strategies to Boost NO	Strategies to boost NO include regular aerobic exercise and dietary supplements like inorganic nitrate, nitrite, l-arginine, and l-citrulline.	[30,31]
Consequences of Excessive Nitrosative Stress	Excessive NO can lead to nitrosative stress, damaging lipids, DNA, and proteins, and is linked to diseases including cardiovascular and neurodegenerative disorders.	[33,34]
Mechanisms to Regulate NO Effects	The body regulates NO effects through protein nitrosation and denitrosylation, underscoring the importance of maintaining balance to support health.	[35]

5. Balancing Exercise-Induced Stress and Antioxidant Defense

5.1. Introduction to the Concept of Hormesis within the Context of Exercise Physiology

Hormesis, a concept in exercise physiology, suggests that moderate oxidative and nitrosative stress from exercise can stimulate beneficial adaptations in the body. This principle is particularly relevant in addressing the increasing prevalence of neurodegenerative diseases in the aging population. Neurohormesis refers to the brain's adaptive responses to low-level stress, showing the potential to slow and mitigate the impact of neurodegenerative conditions. Herbal compounds like resveratrol, curcumin, and sulforaphane have been identified for their neurohormetic effects, activating stress response pathways to enhance cellular defense against injury and improve immune function. These findings suggest promising avenues for managing neurological disorders and supporting healthy aging [36].

The article also touches on the role of reactive oxygen species (ROS) in maintaining cellular redox balance and how shifts toward oxidative stress can contribute to chronic diseases such as cardiovascular issues and cancer. While direct antioxidant supplementation has shown limited efficacy and potential risks, strategies to induce mild oxidative stress, like hormesis, could improve the body's natural defense mechanisms and increase sensitivity to cancer treatments [37]. Key transcription factors, NF-κB and Nrf2, regulate the expression of antioxidant enzymes, demonstrating how low-level stress can enhance health and longevity by triggering protective responses against various stressors [38]. Additionally, the body's adaptation to environmental, physical, and nutritional stress through hormesis involves epigenetic changes, highlighting the importance of understanding these responses for health and longevity. Such adaptations underline the potential benefits of controlled environmental exposures to activate defense mechanisms against diseases and aging [39]. This holistic view of hormesis underscores the intricate balance between stress and adaptive response, offering insights into leveraging these mechanisms for health benefits.

5.2. Strategies for Optimizing the Health Benefits of Exercise While Mitigating Oxidative and Nitrosative Damage

5.2.1. Moderation in Exercise Intensity and Duration

Regular exercise is key to triggering adaptive stress responses and boosting the body's antioxidant defenses, offering numerous health benefits. However, intense or extended physical activity can increase reactive oxygen species (ROS) production, causing oxidative stress in tissues like blood and skeletal muscles, which are major sources of ROS during exercise. This oxidative stress is linked to muscle fatigue and plays a role in muscle adaptation through biochemical signaling. The impact of exercise-induced ROS on health—whether beneficial or harmful—remains debated. The

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body's antioxidant systems, including enzymes like superoxide dismutase, glutathione peroxidase, and catalase, help neutralize ROS and maintain cellular redox balance. A study explored how different intensities and durations of exercise affect oxidative stress and antioxidant responses in sedentary adults. Involving 25 participants, the study found that oxidative stress markers increased after exercise sessions at 50%, 60%, and 70% of peak aerobic capacity across 10, 20, and 30-minute durations, with varied effects on antioxidant enzyme activities. The results suggest that sedentary adults should limit exercise to 70% of their peak capacity. Previous research indicates that exercise-related oxidative stress can promote long-term adaptations and enhance the body's antioxidant capacity. This recent study aids in identifying the most effective exercise intensity and duration for sedentary people, contributing to the broader understanding of exercise's role in health [40,41]. Excessive exercise intensity and duration can lead to oxidative stress, marked by an overproduction of free radicals like Reactive Oxygen Species (ROS) and Reactive Nitrogen Species (RNS), potentially causing cellular damage. While free radicals are a normal part of cellular processes, their accumulation beyond the body's neutralizing capacity can harm proteins, DNA, and lipids, contributing to diseases and accelerating aging. Oxidative stress may also trigger mitochondrial dysfunction and hinder mitochondrial generation, which is particularly significant in aging. To combat oxidative stress, regular physical activity and antioxidants such as quercetin, resveratrol, and curcumin are recommended for their protective effects against the negative impacts on health and aging. Chronic inflammation and oxidative stress are interconnected, leading to various health problems. Effective management of oxidative stress through DNA repair mechanisms, antioxidants like glutathione and superoxide dismutase, and engaging in physical activity are crucial for maintaining cellular health. Structured and moderate exercise is key to mitigating oxidative stress's adverse effects. Research highlights high dropout rates in health clubs, especially within the initial months, with enjoyment a critical factor in exercise persistence. Enjoyment promotes exercise adherence and bridges the gap between intention and actual behavior. The compatibility between an individual's intensity preferences and their actual exercise intensity can influence their enjoyment and, consequently, their exercise habits, intentions, and frequency. A study involving health club participants explored how aligning exercise intensity with personal preferences enhances enjoyment and supports exercise commitment. The findings suggest that when exercise intensity matches personal preferences, it positively affects exercise habits and the desire to continue exercising. These insights are valuable for health club professionals in tailoring exercise programs that maximize adherence by aligning with individuals' intensity traits, thereby enhancing the overall exercise experience [42,43]. This article examines the balance between benefiting from exercise-induced stress adaptations and avoiding oxidative damage, especially in high-intensity exercise, and its link to muscle damage. It focuses on how free radicals contribute to oxidative stress responses. It offers insights for athletes, coaches, and the general populace on recovery tactics from intense workouts and the implications of such activities on athletes' health. The role of antioxidants in aiding the recovery process and mitigating the effects of oxidative stress is highlighted, underscoring their importance in safeguarding cells against damage and preventing oxidative stress-related diseases. The research investigates the impact of different exercise forms on muscle protein leakage and the presence of oxidative stress markers in the blood, stressing the negative consequences of excessive free radical production and the risk it poses through uncontrolled damage within the body. Ultimately, the paper underscores the critical need to understand the interplay between muscle damage and oxidative stress in high-intensity exercise for maintaining overall health and optimizing athletic performance [44]. By customizing exercise intensity and duration based on individual capacities, it is possible to optimize the positive effects of exercise while minimizing the risk of oxidative stress-related harm. This personalized approach can help individuals maintain a healthy exercise routine that promotes overall well-being and long-term fitness goals.

5.2.2. Nutritional Support

A diet rich in antioxidants from fruits, vegetables, and nuts plays a vital role in boosting the body's defense against oxidative stress. This topic continues to be explored in research. Antioxidants

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are essential in protecting the body from damage caused by free radicals. Found naturally in plant-based foods, antioxidants contribute significantly to disease prevention, while industrial antioxidants are used to prevent the oxidation of various products. By neutralizing free radicals and acting as reducing agents, antioxidants are not only integral to supplements in the food industry. However, they are also researched for their potential in combating heart disease and cancer. The antioxidant properties of foods like apples and grains, which may inhibit cancer growth and disease development, underline the importance of further investigation into how the body absorbs and benefits from these compounds [45]. The article also discusses the critical role of antioxidants in eye health, detailing how different molecules protect against oxidative stress in both the anterior and posterior segments of the eye. This protection is crucial for preventing eye disorders like Dry Eye Disease, cataracts, and Age-related Macular Degeneration, among others. Despite ongoing research, the effectiveness of antioxidant supplementation in avoiding eye diseases remains uncertain, calling for more detailed studies [46]. Moreover, the consumption of vitamin C, especially among athletes, is debated regarding its necessity and impact on performance. Vitamin C is crucial for immune health and combating free radicals, but there is evidence that high doses might impede athletic performance by affecting training adaptations and vascular function. For athletes, consuming less than 1g per day and prioritizing vitamin C intake through diet over supplements is advised, with the relationship between vitamin C and athletic performance necessitating further research to optimize dosage and timing [47]. Oxidative stress, characterized by the imbalance between pro-oxidants and antioxidants, underscores the importance of managing this balance to prevent cellular damage and dysfunction [42]. Studies have explored using antioxidants like zinc, selenium, and vitamin C to counteract oxidative stress induced by environmental pollutants like cadmium, highlighting the potential of dietary interventions in mitigating oxidative damage. Incorporating a variety of antioxidants through diet and supplements can help maintain a healthy oxidative balance and support overall well-being [48,49].

5.2.3. Adequate Recovery Periods

Adequate recovery periods are crucial for reducing chronic oxidative stress and aiding the body's repair processes. Research by Mahendra Wahyu Dewangga and Djoko Pekik Irianto investigated how different exercise frequencies affect serum antioxidant levels and muscle damage. Their study divided male Wistar rats into four groups, each subjected to varying weekly exercise frequencies. Findings revealed that exercising four times a week or daily, without sufficient recovery, led to lower serum antioxidant levels and more significant muscle tissue damage. This highlights the importance of including enough rest days in exercise regimes to prevent adverse effects on the body's antioxidant capacity and muscle health [50]. Implementing active recovery techniques and getting enough sleep can significantly enhance recovery and boost antioxidant defenses, helping to offset exercise-induced oxidative stress. In a study exploring how oxidative stress biomarkers fluctuate during exercise and recovery in hot conditions, ten males underwent a cycling exercise in the heat, with blood samples analyzed for oxidative stress indicators. The findings did not confirm the anticipated exercise-induced oxidative stress, which might be attributed to the intense heat stress during rest, delayed recovery, or dehydration effects, with the study's small size possibly affecting results variability. This suggests that more research is necessary to fully grasp the impact of oxidative stress from exercising in hot environments. Another article highlights how strenuous exercise leads to beneficial changes in skeletal muscle, including endurance and strength gains, through processes like mitochondrial biogenesis and muscle hypertrophy. However, these adaptations depend significantly on the recovery phase post-exercise. An imbalance between intense training and insufficient recovery can cause a decline in performance, overreaching, and possibly overtraining syndrome (OTS), characterized by symptoms like prolonged low-frequency force depression (PLFFD) due to muscle damage and glycogen depletion. Reactive oxygen and nitrogen species and inflammatory pathways are likely involved in developing OTS. Identifying the optimal recovery strategies and periods is essential to prevent OTS and support muscle recovery and adaptation [51,52]. Ensuring sufficient recovery time between exercise sessions is crucial for managing oxidative stress,

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facilitating tissue repair, and enhancing overall physiological functions. The autonomic nervous system (ANS) significantly influences health by responding to environmental stressors. An imbalance between the sympathetic (SNS) and parasympathetic (PNS) branches of the ANS can lead to chronic stress and contribute to unhealthy lifestyles prevalent in today's society. This review highlights the ANS network, its interaction with the hypothalamic–pituitary–adrenal axis, and its role in managing immune function, cardiovascular health, oxidative stress, and metabolic imbalances. While physical exercise can positively affect health, high-intensity workouts may induce oxidative stress, affecting the ANS balance. The article underscores the importance of exercise in maintaining an optimal SNS and PNS balance, which helps reduce oxidative stress and inflammation. It also discusses how various brain regions, including the hypothalamus, amygdala, insular cortex, and periaqueductal gray (PAG), regulate autonomic and endocrine responses, influencing emotional behavior and stress reactions [53]. Therefore, incorporating adequate recovery periods into training routines is essential for maintaining optimal health and performance.

5.2.4. Hydration and Electrolyte Balance

Proper hydration and electrolyte balance are essential for optimizing body functions and mitigating oxidative stress during exercise, particularly in hot conditions that increase dehydration risks. A study involving 12 healthy men showed that isotonic drinks were more effective than water in protecting muscles from exercise-induced heat stress, emphasizing the significance of hydration strategies for maintaining performance and recovery, especially under high temperatures [54]. In harsh work environments, such as those faced by agricultural workers in Latin America, the risk of dehydration and related health issues like rhabdomyolysis and acute kidney injury is heightened due to intense labor and climate conditions. Despite recommendations for water intake and rest, the necessity for electrolyte replenishment to maintain hydration and prevent electrolyte imbalances is often overlooked. A trial among sugarcane cutters in Guatemala demonstrated that increased electrolyte intake could maintain hydration and reduce health risks without affecting productivity [55]. Furthermore, data from the National Health and Nutrition Examination Survey highlighted that many U.S. adults do not meet hydration criteria, linking underhydration to chronic diseases and increased mortality rates, underscoring the public health implications of inadequate hydration [56]. The article also discusses the critical role of water in health, exploring water homeostasis, the impact of hydration on performance, and the need for further research on hydration requirements and status monitoring [57]. Ensuring adequate hydration and electrolyte supplementation is thus crucial for health and performance during physical activity and for preventing chronic health conditions. For in-depth insights into the comprehensive strategies for optimizing health benefits and mitigating exercise-induced oxidative and nitrosative stress, refer to Table 3 for a detailed overview.

Table 3. Comprehensive Strategies for Optimizing Health Benefits and Mitigating.

Category	Details	References
Concept of Hormesis	Hormesis in exercise physiology suggests moderate stress from exercise stimulates beneficial adaptations in the body.	[36,37]
Neurohormesis & Neurodegenerative Diseases	Neurohormesis refers to the brain's adaptive responses to low-level stress, showing potential benefits against neurodegenerative diseases.	[36]
Role of Herbal Compounds	Herbal compounds like resveratrol, curcumin, and sulforaphane activate stress response pathways, enhancing cellular defense and immune function.	[36]
Moderation in Exercise	Moderating exercise intensity and duration is critical to triggering adaptive stress responses without causing excessive oxidative damage.	[40,41]

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Impact on Health	The impact of exercise-induced ROS on health is debated; research suggests that oxidative stress can be beneficial in moderation, promoting long-term health adaptations.	[41,44]
Antioxidant-Rich Diet	A diet rich in antioxidants from fruits, vegetables, and nuts supports the body's defense against oxidative stress, contributing to disease prevention.	[45–47]
Importance of Recovery	Adequate recovery periods reduce chronic oxidative stress and aid in the body's repair processes, highlighting the need for sufficient rest between exercise sessions.	[50,51]
Active Recovery Techniques	Active recovery techniques and sufficient sleep enhance recovery and boost antioxidant defenses, helping to offset exercise-induced oxidative stress.	[51,52]
Hydration Strategies	Hydration strategies are essential for maintaining performance and recovery, especially under high temperatures; isotonic drinks may offer benefits over water alone.	[54]
Electrolyte Replenishment	Electrolyte replenishment is crucial in hot conditions or intense labor to maintain hydration and prevent health issues like rhabdomyolysis and acute kidney injury.	[55,56]

6. Nutritional Antioxidants and Exercise

6.1. Investigation into How Diet Influences Exercise-Induced Oxidative and Nitrosative Stress

The research underscores the significance of incorporating antioxidant-rich foods into diets to combat exercise-induced oxidative stress. Studies suggest that whole dietary strategies involving foods like dark chocolate, cocoa, oatmeal, and various fruits and juices can enhance the body's ability to scavenge reactive oxygen species generated during exercise, thereby reducing oxidative stress and inflammation. However, the diverse protocols across these studies call for more standardized research to solidify the evidence supporting the antioxidant benefits of these dietary approaches on exercise-induced oxidative stress [58]. Intense physical activity without adequate recovery can imbalance the body's free radical production and antioxidant defenses, leading to oxidative damage. However, moderate-intensity exercises, such as Taekwondo, have been shown to initiate an adaptive response that improves the body's oxidative balance, emphasizing the importance of exercise type, intensity, and duration in influencing oxidative stress levels and potential cellular damage [59]. Antioxidants from vitamins C and E, selenium, flavonoids, and carotenoids are pivotal in neutralizing harmful reactive species and supporting cellular health during strenuous activities. While supplementation is standard, the correct dosage and timing are crucial to avoid potential pro-oxidant effects and effectively reduce oxidative/nitrosative stress [60].

Diets rich in fruits, vegetables, and whole grains, known for their high antioxidant content, have been linked to improved antioxidant defenses and protection against oxidative stress from exercise. Polyphenols, in particular, found in berries and green tea, may boost antioxidant enzyme activity and lower inflammation and muscle damage markers. The relationship between diet, gut microbiota, and chronic disease development also highlights dietary antioxidants' role in managing conditions like cardiovascular disease and cancer, promoting plant-based diets like the Mediterranean for their preventive benefits. The discussion extends to the potential of polyphenol supplements in enhancing athletes' recovery and performance, though the effectiveness and optimal usage of such supplements require further exploration [61,62]. Thus, a balanced diet rich in natural antioxidants and regular exercise is recommended for mitigating oxidative stress and preventing chronic health issues.

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6.2. Evidence-Based Recommendations for Antioxidant Supplementation to Support Exercise Recovery and Performance

The effectiveness of antioxidant supplementation, exceptionally high doses of vitamin C, for athletic performance and recovery presents mixed results. While some research indicates reduced muscle damage post-exercise, other studies highlight neutral or negative impacts on performance and muscle soreness. Consequently, long-term high-dose vitamin C supplementation is not universally recommended due to inconsistent findings and the potential to dampen training adaptations. Athletes are instead encouraged to focus on a diet rich in nutrients for their antioxidant needs [63]. In addition, antioxidants from natural fruit sources, especially those high in polyphenols, are recognized for their anti-inflammatory and antioxidant capabilities, offering a promising approach to muscle recovery and performance enhancement. Strenuous exercise can disrupt the balance between reactive oxygen species (ROS) and antioxidants, leading to delayed-onset muscle soreness (DOMS), which peaks 24 to 72 hours after activity. Due to their potent properties, fruit-derived antioxidants are explored as effective means to protect muscle cells from ROS-induced damage, showcasing the potential of antioxidant-rich fruit juices in aiding muscle recovery and boosting sports performance. Research on beetroot, grape, and pomegranate juices has shown positive outcomes in minimizing muscle damage and enhancing antioxidant capacity, underlining the role of natural fruit juice supplementation as a viable nutritional strategy for athletes [64]. While the body's natural training adaptations involve ROS, incorporating specific antioxidants like vitamins C, E, and resveratrol can positively contribute to recovery and athletic outcomes.

Vitamin C and E Supplementation: Research on the effects of vitamins C and E on athletic performance and recovery presents mixed outcomes. Some studies highlight the potential of these vitamins to decrease oxidative stress markers and inflammation following intense exercise. However, others caution that high doses might disrupt the body's natural adjustments to training, possibly limiting gains in endurance and strength. The review delves into the impact of antioxidant and vitamin supplementation across various exercise types, including endurance activities and resistance training. Findings generally indicate that such supplementation does not significantly enhance performance, mitigate exercise-induced oxidative stress, or aid recovery. There are concerns that vitamin supplementation could impede the cellular adaptation processes essential for endurance training improvements. The need for further research to clarify the effectiveness and possible downsides of antioxidant and vitamin supplements for athletes is underscored [65,66]. Additionally, a specific focus on the supplementation's impact on delayed-onset muscle soreness (DOMS) through a review of 14 randomized trials involving 280 participants, mostly young, active individuals, reveals that only a few studies reported a notable reduction in muscle soreness from vitamin C and E supplementation. This inconsistent evidence calls for more comprehensive studies to ascertain the role of these antioxidant vitamins in alleviating DOMS.

Polyphenol Supplementation: Polyphenol supplements, such as quercetin and resveratrol, are gaining attention for their potential to boost endurance performance and enhance the body's antioxidant defense mechanisms. These compounds might also aid muscle recovery by reducing inflammation. Although widely used by athletes to minimize exercise-induced oxidative stress and speed up recovery, definitive evidence on the effectiveness of dietary polyphenols for athletes remains sparse. This review examines the bioavailability of polyphenols, their efficacy in combating oxidative stress, and their role in improving athletes' antioxidant status and recovery strategies. Despite indications that polyphenols can bolster antioxidant defenses and mitigate oxidative stress, debates, and mixed results persist regarding their efficacy. The need for further research to pinpoint the effects of polyphenols on oxidative stress, antioxidant status in athletes, and the best dosing practices is highlighted. The review also discusses the significance of standardized polyphenol extracts for more reliable research outcomes, alongside polyphenols' anti-inflammatory properties and contribution to vascular function and recovery enhancement through mechanisms like free radical scavenging and Nrf2 pathway activation. Suggested dosing includes acute supplementation of approximately 300 mg before exercise to boost performance and over 1000 mg daily for several days pre- and post-exercise to aid recovery. However, the complexity of polyphenol absorption and

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metabolism calls for more in-depth studies to validate these recommendations and fully understand polyphenols' potential to support rapid recovery between intensive training sessions or competitions [62,67].

Selenium and Coenzyme Q10: Selenium and coenzyme Q10 (CoQ10) have been studied for their potential to enhance physical performance and reduce oxidative stress. Selenium is crucial for producing glutathione peroxidase (GPX) and thioredoxin reductase (TxnRd), selenoproteins involved in reducing lipid peroxides and regulating cell death, thus maintaining immune homeostasis and heart function. TxnRd, existing in cytosolic and mitochondrial forms, plays roles in DNA synthesis, angiogenesis, and reducing mitochondrial oxidative stress. These selenoproteins also possess anti-inflammatory properties, potentially suppressing the production of inflammatory mediators. However, the pro-inflammatory effects of some selenoproteins suggest a complex role in inflammation regulation, necessitating further research to clarify selenium's mechanisms in immunity and inflammation [68]. CoQ10 is vital for the electron transport chain and antioxidant defense, with natural deficiencies linked to aging and exacerbated by certain medications. At the same time, CoQ10 supplementation has shown promise for cardiovascular health; its effectiveness for statin-associated muscle symptoms varies, indicating the need for more research to establish its benefits across different health conditions [69]. This overview highlights the need for further studies to understand better the impact of selenium and CoQ10 on athletic performance, oxidative stress, and health outcomes. For an in-depth analysis of the enhanced understanding of dietary antioxidants' role in exercise-induced oxidative stress mitigation, refer to Table 4 in our study.

Table 4. Enhanced Understanding of Dietary Antioxidants' Role in Exercise-Induced Oxidative Stress Mitigation.

Category	Details	References
Dietary Strategies & Foods	Incorporating foods like dark chocolate, cocoa, oatmeal, and fruits into diets enhances the ability to reduce exercise-induced oxidative stress through antioxidant-rich diets.	[58,59]
Impact of Exercise Type & Duration	The effectiveness of antioxidants in mitigating oxidative stress varies with the type, intensity, and duration of exercise, emphasizing the need for tailored exercise protocols.	[59,60]
Vitamin Supplementation Effects	Studies on vitamins C and E show mixed results on athletic performance and recovery, suggesting that while beneficial, the effects depend on dosage and individual response.	[63–66]
Polyphenols in Recovery & Performance	Polyphenol supplements, such as quercetin and resveratrol, show potential for improving endurance and recovery by combating inflammation and oxidative stress, but optimal dosing remains to be established.	[62,67]
Specific Roles of Selenium and CoQ10	Selenium and CoQ10 contribute to reducing oxidative stress and enhancing immune and heart function, with a complex interplay in inflammation regulation warranting further study.	[68,69]

7. Discussion

7.1. Integration and Critical Analysis of the Reviewed Literature

Regular, moderate exercise can induce oxidative stress and enhance the body's antioxidant defenses, showcasing a hormetic effect where small amounts of stress can be beneficial [19,70]. The degree of exercise-induced oxidative stress varies with the intensity and quantity of physical activity, with high-intensity aerobic exercises and specific combined training protocols likely to produce significant oxidative stress, especially in unhealthy individuals [3,12,26]. This stress is associated with muscle damage and functional impairments [40], sometimes necessitating antioxidant supplementation to counteract these effects [71]. Moderate continuous aerobic exercise or high-

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intensity interval training is advised to improve redox balance, particularly for those with health issues.

The role of antioxidant supplements, like vitamins C and E, in exercise adaptation generates mixed opinions. While some research indicates these antioxidants could reduce oxidative damage during exercise [72], others suggest that excessive supplementation might inhibit vital physiological responses to training, such as mitochondrial creation and insulin sensitivity [73,74]. Polyphenol antioxidants are recognized for their potential in reducing oxidative stress and muscle damage post-exercise [75]. However, evidence remains mixed, as demonstrated in a study where vitamins C and E did not reduce muscle damage in endurance-trained runners [76]. This indicates a complex relationship between antioxidant supplementation and exercise adaptation, pointing to the need for more research to identify the right balance of supplementation that maximizes performance benefits without compromising training adaptations. Additionally, there is a lack of consensus on the optimal types and amounts of dietary antioxidants for supporting recovery without hindering adaptation, complicated by varied study designs and participant populations.

7.2. Discussion of the Physiological Implications of the Findings for Different Populations

Managing oxidative stress is crucial for optimizing performance and recovery for high-intensity and endurance training athletes. A balanced diet of natural antioxidants is recommended to counteract exercise-induced stress [77,78]. While considering supplementation, athletes should be cautious, as it could impact training adaptations. Tailored nutrition strategies are crucial for athletic performance and recovery, considering individual training demands, dietary needs, and goals [79]. Regular monitoring of oxidative stress and cardiac health biomarkers is beneficial in identifying athletes at risk of suboptimal training responses [80]. Athletes can effectively meet the challenges of intense training and support their health and performance through a diet high in natural antioxidants and customized nutrition plans.

For the general public, regular moderate exercise benefits health and longevity, enhancing antioxidant defenses. Exercise reduces neuroinflammation, maintains cardiovascular health, and facilitates mitochondrial adaptations, particularly beneficial for older adults, including postmenopausal women. Diets rich in natural antioxidant sources, such as fruits, vegetables, soy, fish, and nuts, are essential for health promotion and disease prevention. The focus on natural food sources for antioxidants supports broader dietary guidelines aimed at improving the overall well-being of the general population [81–83].

7.3. Concluding Remarks

The reviewed literature underscores the delicate balance between exercise-induced stress and the body's antioxidant defenses, highlighting the role of diet in modulating these effects. While the benefits of regular physical activity and a nutrient-rich diet are well-established, using antioxidant supplements remains a contentious topic, with the potential for positive and negative impacts on health and exercise adaptation. Future research should clarify these ambiguities, focusing on personalized approaches to diet and exercise that optimize health outcomes across different populations.

8. Conclusion

In conclusion, the intricate dance between exercise-induced oxidative and nitrosative stress and the body's antioxidant defense mechanisms underscores the dual nature of physical activity. While exercise elevates the production of reactive species essential for cellular communication and adaptation, it also risks pushing these levels into cellular damage if not properly managed. The hormesis effect, wherein moderate exercise boosts the body's antioxidant capacity and a diet abundant in natural antioxidants, emerges as a critical strategy in mitigating the potential downsides of physical exertion. This balance between exercise and antioxidant intake is pivotal in harnessing regular physical activity's full health benefits.

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Practically, the pathway to optimizing health and performance lies in adopting a moderate exercise regimen complemented by a balanced, antioxidant-rich diet. Such a regimen safeguards against excessive oxidative stress and supports the body's adaptive responses to physical exertion. Moreover, personalized approaches to nutrition and exercise, informed by professional guidance and careful supplementation, can further refine this balance, enhancing recovery and ensuring that training adaptations are not impeded. Adequate recovery strategies, encompassing hydration, sufficient sleep, and stress management, are indispensable in maintaining this equilibrium, promoting long-term health and peak athletic performance.

The field beckons for more nuanced research that delves into personalized nutrition and exercise interventions, the long-term implications of antioxidant supplementation, and the underpinnings of exercise-induced hormesis. Exploring these avenues across diverse populations, including those with chronic conditions and aging, will enrich our understanding of how to leverage exercise and antioxidants therapeutically. By addressing these gaps in our knowledge, future investigations promise to refine and advance evidence-based practices that optimize the benefits of physical activity through strategic stress management, paving the way for healthier, more resilient bodies.

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