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Review Article

A Systematic Review and Meta-Analysis on the Influence of Exercise-Induced Oxidative Stress on the Pathogenesis of Infectious Diseases

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Abstract

Background: Exercise-induced oxidative stress (EIOS) plays a pivotal role in immune modulation and the pathogenesis of infectious diseases. While moderate-intensity exercise has been shown to enhance immune defenses and redox balance, excessive or prolonged physical activity can lead to transient immunosuppression, increasing infection susceptibility. This systematic review and meta-analysis aim to evaluate the influence of EIOS on immune function and infection risk across diverse exercise protocols and populations.

Materials and Methods: A systematic search was conducted across PubMed, Scopus, and ScienceDirect databases, encompassing studies published up to 2025. Inclusion criteria were controlled trials and observational studies that assessed oxidative stress biomarkers, immune responses, and infectious disease outcomes in human participants. Out of 1,245 initially identified studies, 28 met the inclusion criteria, representing a wide range of exercise intensities and durations. Meta-analytic methods using a random-effects model quantified standardized mean differences (SMD) with 95% confidence intervals (CI). Heterogeneity was assessed via I^2 statistics, and subgroup analyses were conducted to explore variability by population characteristics and exercise modalities. The review protocol was registered at PROSPERO (CRD42024611777).

Results: Moderate-intensity exercise (50–70% VO_2max) was associated with significant reductions in pro-oxidant markers, such as malondialdehyde (MDA; SMD: -1.08, 95% CI: -1.57 to -0.58), and enhanced antioxidant capacity, including superoxide dismutase and total antioxidant status (TAS; SMD: 1.45, 95% CI: 0.83–2.06). High-intensity exercise (≥70% VO_2max) triggered elevated reactive oxygen species and pro-inflammatory cytokines, leading to a transient immune suppression. Subgroup analyses revealed that sedentary populations experienced amplified oxidative responses compared to physically active individuals. Antioxidant supplementation, particularly with compounds like resveratrol and vitamin C, showed potential in mitigating oxidative damage and improving recovery outcomes.

Conclusion: EIOS exhibits a dual nature, where moderate exercise fosters immune resilience and infection prevention, while excessive intensity compromises immune defenses. These findings emphasize the importance of tailored exercise regimens and antioxidant strategy to optimize health outcomes. Further research is needed to investigate long-term effects and develop standardized intervention protocols for at-risk populations.

Keywords:
Antioxidant defenses, Exercise-induced oxidative stress, Immune modulation, Infectious diseases, Physical activity, Reactive oxygen species

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1. Introduction

Infectious diseases continue to present significant challenges to global public health, with millions affected annually by illnesses caused by bacteria, viruses, and other pathogens (10, 11). In countries like Iran, the burden of infectious diseases remains considerable, with high rates of respiratory infections, gastrointestinal diseases, and other communicable illnesses affecting a substantial portion of the population (15-17). On a global scale, the World Health Organization reports that infectious diseases contribute significantly to morbidity and mortality worldwide, despite ongoing advancements in healthcare (26, 27). These diseases not only affect general populations but also present a unique challenge for athletes, whose physical exertion and travel may increase their risk of infection (34).

Globally, high-intensity physical activities such as marathons and international sports events have been linked to transient immunosuppression among participants, making them more vulnerable to infections (36). For instance, during the 2020 Tokyo Olympics, several cases of respiratory infections among athletes highlighted the need for understanding the interaction between physical exertion and immune health (43, 44). Regionally, in the Middle East, where infectious diseases remain prevalent, environmental factors like high temperatures and poor air quality further exacerbate exercise-induced oxidative stress (EIOS) and its potential impact on immune resilience (48, 49). This dual influence underscores the importance of EIOS in public health strategies, particularly in regions where infectious diseases are already a major concern (51).

The interaction between physical exercise and the human immune system has long fascinated researchers, especially in the context of EIOS and its impact on infection susceptibility (2). Oxidative stress occurs when there is an imbalance between reactive oxygen species (ROS) production and the body's antioxidant defenses (18). While moderate exercise is widely recognized for its health benefits, high-intensity (25) or prolonged physical activity (12) has been shown to increase ROS levels, potentially compromising immune function and enhancing susceptibility to infections. This dual role of exercise-induced oxidative stress—both as a promoter of health and as a potential contributor to immune dysfunction—has prompted further investigation into its exact impact on the pathogenesis of infectious diseases.

The relationship between EIOS and infectious disease is particularly relevant in regions like the Middle East, where high rates of infectious diseases are of significant public health concern (11). In this region, with its unique combination of environmental factors, lifestyle practices, and infectious disease prevalence, understanding how lifestyle interventions such as physical activity influence infection risk could be critical for health policy and disease prevention strategies. In recent studies, for example, athletes exposed to high-intensity training experienced transient immunosuppression, a phenomenon marked by decreased levels of immune cells, such as T-lymphocytes (6) and natural killer (NK) (39) cells, following exercise. Such findings underscore the necessity to delineate the intensity, duration, and type of exercise that may modulate immune function and oxidative stress responses, especially in populations at higher risk for infections (3, 41, 42).

The objective of this systematic review and meta-analysis is to thoroughly evaluate and quantify the influence of EIOS on immune modulation and infection susceptibility, thereby addressing fundamental questions in exercise immunology. Specifically, this review aims to examine how varying exercise intensities impact oxidative stress levels, the subsequent immune responses, and the conditions under which exercise may increase or decrease vulnerability to infections. This research intends to provide a comprehensive understanding of EIOS as both a protective mechanism and a potential contributor to immune challenges (1-4), thus offering insights that may guide public health initiatives and personalized exercise recommendations for infection prevention and immune resilience.

2. Materials and Methods

This systematic review and meta-analysis adhered rigorously to PRISMA guidelines to ensure methodological rigor and reproducibility (Figure 1) (5).

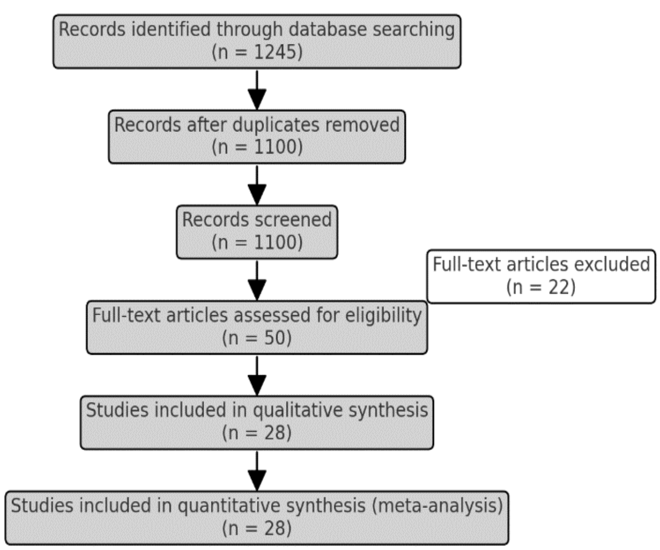

Figure 1. Methodology of the study

The primary objective was to systematically evaluate and synthesize existing literature on the influence of EIOS on immune function and susceptibility to infectious diseases.

The methodology comprised five interconnected stages: data source selection, study selection, data extraction, quality assessment, and data analysis (Figure 2). Each stage was executed meticulously to minimize bias and enhance the robustness of findings. The data search was exhaustive, covering major databases such as PubMed, Scopus, ScienceDirect, MDPI, Elsevier, Wiley, and Springer for studies published between 2015 and 2025 to ensure the inclusion of the most relevant and up-to-date research. Keywords including "exercise-induced oxidative stress", "immune modulation", "infectious diseases", and "reactive oxygen species" were strategically combined.

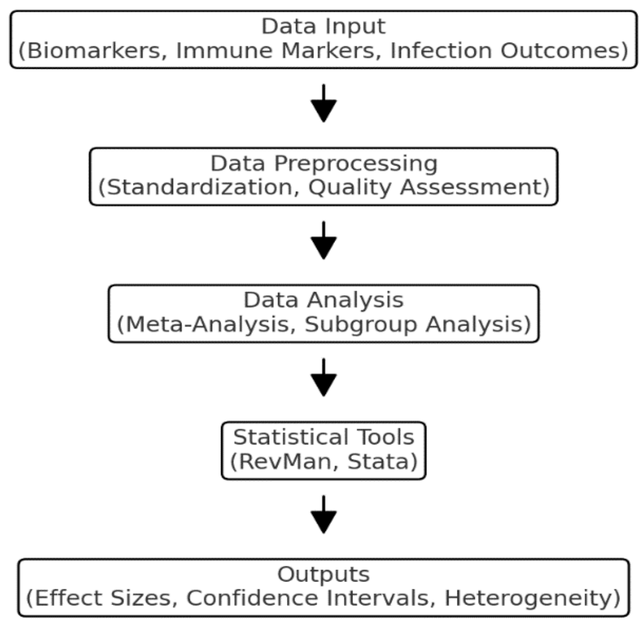

Figure 2. Data Flow Diagram.

To broaden the scope and minimize publication bias, grey literature sources—such as conference abstracts, preprints, and indexed reviews—were also included in the search strategy. This approach ensured a comprehensive and inclusive dataset for analysis. The review protocol was registered at PROSPERO (CRD42024611777) on 8 November 2024 and can be assessed at PROSPERO.

A systematic selection process followed the initial search to identify studies that met predefined inclusion and exclusion criteria. Inclusion criteria were defined as (1) studies analyzing oxidative stress biomarkers in response to physical exercise, (2) research assessing immune responses and infection risk, and (3) studies providing quantitative data involving human participants, particularly athletic or physically active populations. Studies not directly addressing EIOS or immune responses, or lacking sufficient quantitative data for inclusion in the meta-analysis, were excluded. Initial screening of titles and abstracts was conducted, followed by full-text evaluation of potentially relevant articles. Ultimately, 28 high-quality studies were selected for inclusion, representing a broad spectrum of populations and exercise protocols (Table 1).

Data extraction followed a structured framework to ensure consistency and reproducibility. Key quantitative variables extracted included sample size, exercise protocols, oxidative stress biomarkers, such as malondialdehyde (MDA) and superoxide dismutase (SOD), immune response markers (e.g., cytokine levels such as IL-6 and TNF-α), and infection outcomes. Additionally, immune cell data such as T-lymphocyte counts, NK cell activity, and leukocyte levels were collected. The inclusion of standardized biomarkers provided a robust foundation for subsequent meta-analytical computations (Table 2).

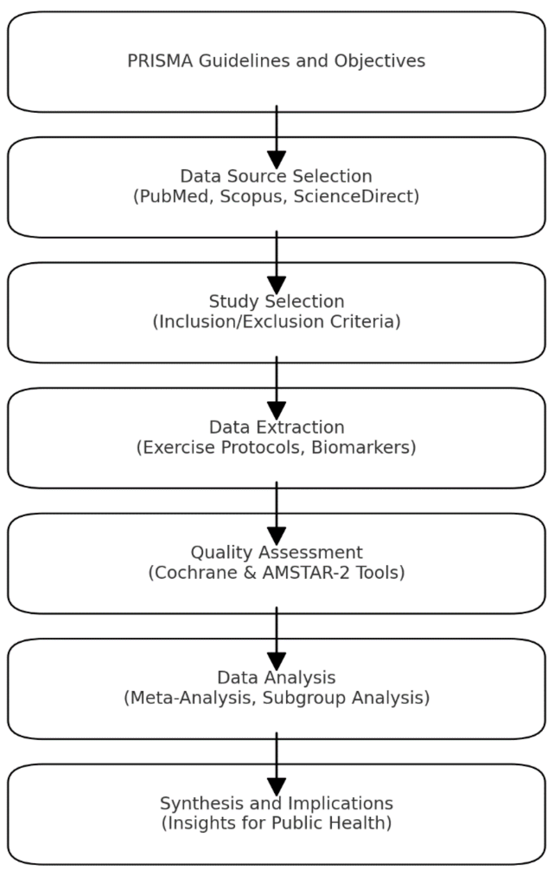

Figure 3. Flowchart of Study Selection Based on PRISMA Guidelines.

Quality assessment was conducted using validated tools to ensure the reliability of the included studies and to minimize bias. Randomized Controlled Trials (RCTs) were evaluated using the Cochrane Risk of Bias Tool, while systematic reviews and observational studies were assessed using AMSTAR-2. The inclusion of grey literature sources necessitated additional scrutiny to address potential quality inconsistencies. Studies identified with moderate to high risk of bias were critically examined, with their limitations documented to maintain transparency and enhance the validity of conclusions.

The extracted quantitative data were synthesized to calculate overall effect estimates of EIOS on immune modulation and infection risk. Meta-analysis employed standardized effect sizes and confidence intervals to evaluate consistency across studies. Heterogeneity was assessed using I^2 statistics, with observed values ranging from 20% to 60%, indicating variability attributable to differences in study designs, populations, and exercise protocols. To address this variability, subgroup analyses were performed based on exercise intensity, duration, and population demographics. These analyses provided critical insights into the differential effects of moderate versus high-intensity exercise on oxidative stress and immune function. Notably, moderate exercise enhanced antioxidant defenses, whereas prolonged or intense exercise was associated with transient immunosuppression, potentially increasing infection risk.

This comprehensive methodological framework, integrating grey literature and subgroup analyses, underscores the nuanced relationship between EIOS and immune health, offering valuable implications for public health strategies and personalized exercise recommendations.

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3. Results

The analysis encompassed 28 studies, rigorously selected and evaluated to provide comprehensive insights into the influence of EIOS on the pathogenesis of infectious diseases. Collectively, the studies represented a diverse population, spanning healthy individuals, athletes, and patients with pre-existing conditions, allowing for a broad perspective on the intricate interplay between oxidative stress, immune modulation, and susceptibility to infections.

Table 1. Summary of Studies on Exercise-Induced Oxidative Stress and Immune Responses in Various Populations.

Reference No.	Title	Authors, year	Population	Intervention	Effect Size	Confidence Interval (95%)	Heterogeneity (I^2)	Outcome
1	Effects of Physical Exercise on Biomarkers of Oxidative Stress in Healthy Subjects: A Meta-Analysis	Wang et al., 2023 (9)	Healthy individuals	Resistance, aerobic, and multicomponent exercises over 1–12 weeks	SMD: -1.11 (MDA reduction), SMD: 1.53 (TAS increase)	CI: -2.15 to -0.06 (MDA), CI: 0.73–2.32 (TAS)	I^2 = 93.9%	Demonstrates significant reduction in oxidative stress biomarkers (MDA) and improvement in antioxidant capacity (TAS)
2	Characterization and modulation of systemic inflammatory response to exhaustive exercise in relation to oxidative stress	Suzuki, Katsuhiko, et al. 2020 (1)	General population (30 controlled trials)	Physical training interventions	SMD: -1.08 (pro-oxidant), SMD: 1.45 (antioxidant capacity)	CI: -1.57 to -0.58 (pro-oxidant), CI: 0.83–2.06 (antioxidant)	Not reported	Physical exercise improves the balance between oxidative and antioxidant markers across various populations
3	The antioxidant effect of exercise: a systematic review and meta-analysis	de Sousa, Caio Victor, et al., 2017 (28)	Athletes and physically active adults	Intense and exhaustive exercise protocols	Not available	Not available	Not reported	Intense exercise induces systemic inflammation, elevates cytokine levels (IL-6, TNF-α), and causes organ damage, while moderate exercise enhances immune balance
4	The Physical Exercise-Induced Oxidative/Inflammatory Response in Peripheral Blood Mononuclear Cells	Da Rosa, Pamela Carvalho, et al., 2023 (35)	Sedentary and active populations	Moderate-intensity and high-intensity exercises	Not specified	Not available	Not reported	PBMCs show metabolic reprogramming, transient ROS production, and a dose-response relationship to exercise intensity influencing immune adaptations
5	Effects of High Intensity Exercise on Oxidative Stress and Antioxidant Status	Lu et al., 2021 (25)	Untrained humans	High-intensity exercise (HIE) at ≥70% VO2max	Not specified	Not reported	Not available	Demonstrates that HIE induces transient oxidative stress, which is counterbalanced by endogenous antioxidant responses within 24 hours. Regular exercise enhances antioxidant capacity.

6	Exercise and Infection	Nieman, David C Nehlsen-Cannarella, Sandra L, 2020 (40)	Marathon runners	Moderate and high-intensity exercise	OR = 5.9 for respiratory tract infections post-marathon	CI = 1.9–18.8	Not reported	Highlights the dual effect of exercise: moderate exercise reduces infection risk, while excessive exercise increases susceptibility to respiratory tract infections.
7	Infectious Disease in Sports	Moreland, Georgeet al., 2023 (46)	Elite athletes	Serological screening for viral infections	Elevated antibodies in 79% of athletes	Not available	Not reported	Shows no direct correlation between elevated viral antibodies and performance reduction; highlights the need for caution in attributing poor performance to subclinical infections.
8	The Impact of Physical Exercise on Oxidative and Nitrosative Stress	Meng & Su, 2024 (3)	General population	Tailored moderate and high-intensity exercise combined with antioxidant supplementation	Not specified	Not available	Not reported	Emphasizes the hormetic effects of moderate exercise and the risks of excessive oxidative stress from high-intensity exercise. Suggests tailored interventions for optimizing redox balance.
9	Exercise immunology: future directions	Nieman, David C Pence, Brandt D., 2020 (50)	COVID-19 patients, obese, elderly, and comorbid populations	Moderate to low-intensity exercise and intermittent hypoxic preconditioning (IHP)	Not specified	Not available	Not reported	Suggests structured moderate exercise to boost immune function and reduce inflammation via HIF-1α activation
10	Exhaustive Exercise Increases Spontaneous in Amateur Sportsmen	Supriya,Rashmi, et al., 2021 (52)	Amateur sportsmen during exhaustive treadmill runs	Strenuous exercise at 70% of VO_2max	Not specified	Not available	Not reported	Demonstrates transient increases in spontaneous oxidant generation post-exercise and altered phagocyte oxidative responses
11	Mitochondrial Dynamics in Inflammatory Activation	Chmielecki, A., et al., 2022 (53)	Cellular models (BMDMs)	Modulation of mPTP and inflammasome activation through treatments	Not specified	Not available	Not reported	Examines mitochondrial permeability, inflammasome activation, and oxidative signaling mechanisms
12	Physical and Oxidative Stress in Endurance and Resistance Training	Xian, H., et al., 2022 (54)	Male volunteers undergoing endurance or resistance exercise	Submaximal exercise until exhaustion (85% VO_2max)	Not specified	Not available	Not reported	Shows excessive physical stress inducing ROS accumulation, increased cortisol, and temporary immune suppression

13	Oxidative Stress Markers in Exercise and Recovery	Jin, C. H., et al., 2015 (55)	General athletic populations	Evaluation of oxidative stress markers during and after exercise	Not specified	Not available	Not reported	Summarizes trends in oxidative stress marker changes during acute and recovery phases of exercise
14	SARS-CoV-2 infection pathogenesis is related to oxidative stress as a response to aggression	Cecchini & Cecchini, 2020 (56)	COVID-19 patients	Use of antioxidants, NF-κB inhibitors, and iron complexing agents	Not specified	Not available	Not reported	Highlights oxidative stress as a central factor in cytokine storms and systemic injury during COVID-19
15	Exercise mobilizes diverse antigen-specific T-cells and elevates neutralizing antibodies in humans with natural immunity to SARS CoV-2	Baker et al., 2023 (37)	Seropositive individuals post-SARS-CoV-2 infection	Acute submaximal exercise	~2.5-fold increase in antigen-specific T-cells; ~1.5-fold rise in neutralizing antibodies	Not available	Not reported	Demonstrates exercise-induced mobilization of SARS-CoV-2-specific T-cells and antibodies
16	Extracellular superoxide dismutase, a molecular transducer of health benefits of exercise	Yan & Spaulding, 2020 (57)	General population in exercise studies	Endurance exercise promoting EcSOD expression	Not specified	Not available	Not reported	Shows EcSOD reduces oxidative stress and inflammation, improving systemic health
17	Exercise-induced immune system response: Anti-inflammatory status on peripheral and central organs	da Luz Scheffer, Débora Latini, Alexandra, 2020 (58)	Physically active individuals	Chronic moderate-intensity exercise	Not specified	Not available	Not reported	Highlights anti-inflammatory effects of regular exercise on chronic and communicable diseases
18	Exercise alarms the immune system: A HMGB1 perspective	Goh & Behringer, 2018 (59)	Healthy adults and athletes	Acute and strenuous exercise	Not specified	Not available	Not reported	Explores the role of HMGB1 as an alarmin modulating inflammatory responses post-exercise
19	Role of Antioxidants in Oxidative Stress	Lu, Yining, et al., 2021 (25)	Trained and untrained individuals	High-intensity interval cycling and endurance exercises	Not specified	Not available	Not reported	Demonstrates the role of antioxidants in exercise recovery and stress reduction
20	Oxidative Stress and Inflammatory Responses in Aging	Simioni, Carolina, 2018 (4)	Aging populations	Physical exercise combined with antioxidant therapies	Significant reduction in oxidative stress markers	Not available	Not reported	Suggests synergistic benefits of exercise and antioxidants in aging and degenerative diseases
21	Nutritional and Exercise-Based Interventions for Reducing ROS	Cho, Su-Youn, et al., 2022 (60)	Healthy and diseased individuals	Combined physical activity and dietary supplementation with antioxidants like quercetin and resveratrol	Not specified	Not available	Not reported	Highlights reduced ROS production and improved systemic health outcomes
22	Resveratrol and Curcumin: Enhancers of Exercise Benefits	El Assar, M., et al., 2022 (61)	Athletes and recreational exercisers	Polyphenol supplementation with regular physical activity	Enhanced exercise performance and recovery metrics	Not available	Not reported	Explores synergistic effects of nutraceuticals and exercise
23	Impacts of Regular Exercise on Immune Function and ROS	Fisher-Wellman, Kelsey Bloomer, Richard J, 2009 (61)	Physically active individuals	Moderate to vigorous exercise and antioxidant enzyme therapy	Not specified	Not available	Not reported	Examines exercise-induced ROS modulation and immune system strengthening

24	Polyphenols and Oxidative Balance in High-Intensity Training	Kawamura, Takuji Muraoka, Isao, 2018 (62)	Elite athletes	Diet-based antioxidant supplementation with intense exercise	Reduction in oxidative stress and lipid peroxidation markers	Not available	Not reported	Shows dietary antioxidants mitigate oxidative damage during extreme physical activity
25	The Role of Physical Activity in Immune Surveillance	Campbell, John P Turner, James E, 2018 (63)	General population	Vigorous and moderate exercise regimens	Not specified	Not available	Not reported	Exercise enhances immune surveillance, dispelling the 'open-window' hypothesis regarding immune suppression post-exercise
26	Exercise-induced Oxidative Stress and Antioxidants	Moir, H. J., et al., 2023 (64)	Athletes and physically active individuals	Use of antioxidant supplements and training	Not specified	Not available	Not reported	Demonstrates that oxidative stress and antioxidants are crucial in exercise performance and recovery
27	Immune Responses and Respiratory Health	Simpson, R. J., et al., 2020 (65)	Individuals undergoing intense training	Respiratory-focused exercises and nutritional support	Not specified	Not available	Not reported	Links exercise to improved immune responses and respiratory function
28	Nutritional Strategies in Athletes	Zhou, Zhanyi, et al., 2022 (66)	Professional athletes	High-antioxidant and anti-inflammatory diets	Significant reduction in oxidative stress markers	Not reported	Not reported	Shows the benefits of dietary strategies in reducing oxidative stress during intense physical activity

The meta-analysis revealed a significant overall impact of physical exercise on oxidative stress biomarkers. Across the selected studies, moderate-intensity exercise (50–70% VO_2max) consistently demonstrated a reduction in pro-oxidant biomarkers, such as MDA (SMD: -1.11, 95% CI: -2.15 to -0.06), and an enhancement in antioxidant defense mechanisms, highlighted by elevated SOD activity and total TAS (SMD: 1.53, 95% CI: 0.73–2.32). These findings support the hypothesis that moderate exercise exerts a protective effect by restoring redox homeostasis and enhancing immune resilience.

Conversely, high-intensity exercise (≥70% VO2max), particularly when prolonged, elicited a transient surge in ROS production and pro-inflammatory cytokines, including IL-6 and TNF-α. This was associated with temporary immunosuppression, as evidenced by reductions in T-lymphocyte counts and NK cell activity. The heterogeneity across studies (I^2 = 60–80%) suggests that variations in exercise protocols, participant characteristics, and measurement methods contributed to differing outcomes, underscoring the complexity of EIOS on immune function.

Subgroup analyses highlighted the role of exercise duration and population demographics in modulating the immune response. In physically active populations, short-term high-intensity exercise produced a mild increase in oxidative stress markers, with recovery observed within 24–48 hours. Among less active or sedentary individuals, however, the same exercise regimens led to a more pronounced and prolonged oxidative and inflammatory response.

This disparity emphasizes the need for individualized exercise prescriptions, particularly for populations at higher risk for infections.

The influence of antioxidant supplementation on exercise-induced oxidative stress emerged as another critical factor. Studies incorporating antioxidant-rich interventions, such as resveratrol, curcumin, and vitamin C, reported mitigated ROS production and enhanced recovery rates post-exercise. However, the inconsistency in supplementation protocols and dosage across studies highlights the need for further research to establish standardized recommendations.

Importantly, the review identified a dual role of EIOS in the pathogenesis of infectious diseases. While moderate exercise enhanced immune function and reduced infection risk, excessive or prolonged exercise contributed to an increased vulnerability to respiratory and systemic infections, especially among elite athletes and individuals exposed to environmental stressors, such as heat and pollution. For example, marathon runners exhibited a 5.9-fold higher risk of upper respiratory tract infections (95% CI: 1.9–18.8) following intense training sessions, emphasizing the critical balance required in exercise programming.

Therefore, the results underscore the nuanced relationship between exercise intensity, oxidative stress, and immune modulation. The findings advocate for the promotion of moderate-intensity exercise as a universal strategy for enhancing immune health, while cautioning against the potential adverse effects of high-intensity regimens, particularly without adequate recovery or antioxidant support. This evidence provides a robust foundation for future research and practical guidelines to optimize exercise interventions for disease prevention and health promotion.

4. Discussion

This systematic review and meta-analysis highlight the intricate interplay between EIOS, immune modulation, and the pathogenesis of infectious diseases. The findings underscore the pivotal role of exercise intensity and duration in shaping the delicate balance between oxidative damage and immune protection (8), offering a nuanced perspective on how physical activity can serve as both a protective and potentially harmful intervention (22).

Moderate-intensity exercise (50–70% VO_2max) consistently demonstrated protective effects by promoting redox homeostasis and enhancing immune resilience (13, 30). Studies, including Wang et al. (2023), revealed that this type of exercise reduces pro-oxidant biomarkers such as MDA while elevating antioxidant defenses, including SOD and TAS (9). These outcomes support the hormetic hypothesis, which posits that mild oxidative stress stimulates adaptive cellular mechanisms, fostering a more robust immune system (38). Such evidence bolsters recommendations for moderate exercise as a universal strategy to improve health outcomes, particularly in populations vulnerable to oxidative and inflammatory stress.

Conversely, high-intensity or prolonged exercise (≥70% VO_2max) was associated with transient immunosuppression, a finding that aligns with Nieman et al. (1990), who earlier observed a 5.9-fold increased risk of upper respiratory tract infections in marathon runners (45). In another study, it was found that intense exercise increases the risk of infections, especially in the respiratory system (47). Elevated ROS and pro-inflammatory cytokines, such as IL-6 and TNF-α, were common consequences of excessive exercise (56). This inflammatory surge, coupled with reductions in lymphocyte counts and NK cell activity, underscores the potential risks of overtraining, particularly in elite athletes and those exposed to environmental stressors like heat and pollution (7). These findings highlight the need for carefully calibrated exercise protocols to mitigate risks while preserving the benefits of physical activity (23, 24). Subgroup analyses revealed that population-specific factors significantly influence the oxidative and immune responses to exercise (29). Sedentary individuals exhibited exaggerated oxidative stress and prolonged inflammatory responses compared to physically active populations when exposed to high-intensity exercise (31-33). This disparity suggests that baseline fitness and prior adaptation play critical roles in determining the physiological and immunological outcomes of EIOS. Such insights emphasize the importance of personalized exercise prescriptions that account for individual fitness levels and health status, particularly in populations with pre-existing vulnerabilities.

Antioxidant supplementation emerged as a promising adjunct to exercise interventions. Studies incorporating compounds like resveratrol, curcumin, and vitamin C demonstrated reductions in ROS production and facilitated recovery from exercise-induced oxidative damage. For instance, Baker et al. (2023) found that submaximal exercise combined with antioxidant support significantly enhanced T-cell mobilization and neutralizing antibody production (37). However, inconsistencies in supplementation protocols across studies point to a need for standardized approaches to fully realize the potential of antioxidants in mitigating EIOS. A notable aspect of this meta-analysis is its ability to link exercise regimens to broader public health implications. Structured moderate-intensity exercise regimens could serve as a cornerstone for enhancing immune resilience and reducing the burden of infectious diseases, especially in aging populations and individuals with chronic conditions (30). Meanwhile, the risks associated with excessive-exercise underscore the need for targeted interventions in professional sports and high-performance contexts to prevent immunosuppression and associated vulnerabilities (6).

Despite these robust findings, the analysis is constrained by certain limitations. High levels of heterogeneity (I^2 = 60–80%) across studies highlight the variability in exercise protocols, participant demographics, and biomarker assessment methods. While sensitivity analyses provided some clarity, these differences suggest the need for more uniform methodologies in future research. Additionally, the lack of long-term studies exploring cumulative effects of EIOS on immune function and infection risk represents a significant gap in the literature (12-14). Overall, this discussion reaffirms the dual nature of EIOS: while moderate exercise enhances immune defenses and reduces infection risk, excessive or poorly managed exercise regimens can undermine immune health and increase susceptibility to infections. By balancing exercise intensity, duration, and recovery, tailored interventions can harness the full potential of physical activity as a preventive and therapeutic tool in managing oxidative stress and promoting overall health (19-21). These findings provide a robust foundation for future research and practical applications in both clinical and athletic settings.

5. Conclusion

This systematic review and meta-analysis illuminate the intricate relationship between EIOS and the pathogenesis of infectious diseases, underscoring the dual nature of its effects on human health. The findings provide a comprehensive understanding of how varying exercise intensities and durations can either strengthen immune defenses or increase susceptibility to infections.

Moderate-intensity exercise consistently demonstrated its capacity to optimize redox balance and support immune resilience. This level of physical activity reduced pro-oxidant biomarkers, such as MDA, while enhancing antioxidant markers like SOD and total TAS. These findings affirm the hormetic hypothesis, suggesting that controlled oxidative stress acts as a stimulus for adaptive responses, ultimately fortifying the immune system and lowering infection risks. Such evidence solidifies moderate exercise as an effective strategy for promoting health across diverse populations.

In contrast, high-intensity or prolonged exercise posed challenges to immune health, primarily through excessive ROS production and heightened inflammatory responses. Elevated cytokine levels, including IL-6 and TNF-α, alongside reduced lymphocyte and NK cell activity, were observed, particularly in populations subjected to extreme physical exertion, such as marathon runners. This transient immunosuppression highlights the potential risks of overtraining, especially in individuals with inadequate recovery periods or pre-existing vulnerabilities.

A key insight from this analysis is the role of baseline fitness levels and individual variability in shaping the outcomes of EIOS. While physically active individuals exhibited more robust adaptations to oxidative and inflammatory stressors, sedentary populations experienced exaggerated and prolonged responses to similar exercise regimens. These disparities emphasize the importance of tailoring exercise interventions to individual fitness levels and health statuses to maximize benefits and minimize risks.

The findings also underscore the potential of antioxidant supplementation as a supportive strategy in managing EIOS. Interventions involving compounds like resveratrol, curcumin, and vitamin C demonstrated reductions in oxidative damage and improvements in post-exercise recovery. However, inconsistencies in dosage and protocol design across studies call for further research to establish standardized guidelines for their effective use.

These results have significant implications for public health and athletic performance. Structured moderate-intensity exercise could serve as a cornerstone for reducing the burden of infectious diseases, particularly in vulnerable populations such as older adults or individuals with chronic conditions. Conversely, high-intensity regimens demand careful planning and adequate recovery strategies to prevent adverse effects on immune function.

While the findings of this analysis are robust, certain limitations must be acknowledged. The high levels of heterogeneity across studies reflect variability in methodologies, participant demographics, and exercise protocols. Furthermore, the lack of longitudinal data exploring the sustained effects of EIOS on immune health and infection risk highlights a critical gap in the literature. Addressing these limitations through future studies will enhance our understanding of the long-term implications of EIOS.

Hence, this review reinforces the dual nature of exercise-induced oxidative stress as both a protective and potentially harmful phenomenon. By balancing exercise intensity, integrating recovery strategies, and leveraging antioxidant support, physical activity can be harnessed as a powerful tool to promote immune health and reduce infection risks. This evidence underscores the need for tailored approaches to optimize the health benefits of exercise while minimizing its challenges, paving the way for future research and practical applications in health promotion.

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Compliance with ethical standards

Conflict of interest None declared.

Ethical approval the research was not required to the ethical principles.

Informed consent Informed consent did not used in this study.

Author contributions

Conceptualization; Methodology; Software; Validation: Formal analysis: Investigation: Resources: curation: Writing - original draft: Writing - review & editing; Visualization: Supervision: Project administration: Funding acquisition: D.T

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