CZARNOTA, Maksymilian, OSSOWSKA, Weronika and ÖSZTREICHER, Wiktoria. Gut Microbiota Modulation to Enhance Exercise Performance and Recovery - Systematic Review. Quality in Sport. 2025;43:62420. eISSN 2450-3118.
https://doi.org/10.12775/QS.2025.43.62420
https://apcz.umk.pl/QS/article/view/62420

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. This is according to the Annex to the announcement of the Minister of Higher Education and Science dated 05.01.2024, No. 32553. The journal has a Unique Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).
The authors declare that there is no conflict of interest regarding the publication of this paper.
Received: 15.06.2025. Revised: 05.07.2025. Accepted: 05.07.2025. Published: 10.07.2025.

Gut Microbiota Modulation to Enhance Exercise Performance and Recovery - Systematic Review

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Abstract

Background: Recent evidence suggests that the gut microbiota can influence host metabolism, immunity, and tissue repair—processes critical for exercise performance and recovery.
Objective: To synthesise human research examining whether modulation of the gut microbiota—via probiotics, prebiotics, diet, or training—affects physical capacity and post-exercise recovery.
Methods: A systematic search of PubMed and Scopus (until May 2025) identified peer-reviewed human studies involving gut-directed interventions or athlete comparisons reporting on physical performance, fatigue, immune response, or gut integrity. Thirty-five studies met inclusion criteria and were narratively analysed.
Results: Regular endurance or mixed training increased microbial diversity, SCFA-producing taxa, and gut-barrier integrity, while excessive loads reduced diversity and increased permeability. Multi-strain probiotic or synbiotic supplementation ($\geq 10^{10}$ CFU/day, $\geq$4 weeks) improved endurance, reduced muscle-damage markers, and lowered illness incidence during intense training. Fibre-rich diets enhanced beneficial taxa and reduced inflammation.
Conclusions: Modulating the gut microbiota is a promising adjunct to training and nutrition strategies. Periodised probiotic use, sustained fibre intake, and personalised gut-health monitoring may optimise performance and recovery. Further well-designed, long-term trials are needed to clarify causality and refine recommendations.

Keywords: Gut microbiota; Exercise performance; Recovery; Probiotics; Prebiotics; Athletes; Sports nutrition; Short-chain fatty acids (SCFAs); Microbiome modulation; Physical endurance

1. Introduction

Over the past decade, the gut microbiota has emerged as a dynamic and multifaceted component of human physiology, with far-reaching implications beyond gastrointestinal health. The gut ecosystem—composed of trillions of bacteria, archaea, viruses, and fungi—plays a pivotal role in modulating systemic immunity, metabolism, neuroendocrine signaling, and barrier function.

These microbiota-host interactions are increasingly recognized as relevant not only in disease prevention but also in optimizing physiological performance in healthy individuals, including athletes [1,3,25].

In the context of sports and physical activity, the concept of the "athletic gut microbiota" has gained considerable attention. Athletes demonstrate a distinct gut microbial profile compared to sedentary individuals, characterized by higher microbial diversity, enrichment of short-chain fatty acid (SCFA)-producing bacteria, and altered metabolic potential [3,28,35]. These variations are not merely reflective of lifestyle differences but may actively contribute to exercise-related adaptations such as improved energy utilization, enhanced anti-inflammatory responses, and more efficient recovery from exertion [3,6,12].

Experimental and translational studies have provided compelling evidence that targeted modulation of the gut microbiota—via probiotics, dietary strategies, and training stimuli—can influence endurance, fatigue resistance, immune resilience, and gastrointestinal function in physically active populations [13,14,17,24,26]. Mechanistically, this may be mediated through microbial production of SCFAs, regulation of intestinal permeability, and interactions with muscle metabolism and mitochondrial function [18,20,34]. However, despite this growing body of knowledge, the translation of these findings into evidence-based interventions for performance enhancement remains in its infancy.

From a clinical and applied perspective, optimizing gut health may offer a novel avenue to enhance both acute exercise capacity and post-exercise recovery. This is particularly relevant in high-performance settings where gastrointestinal disturbances, chronic low-grade inflammation, and compromised immune function can hinder training continuity and competitive success [13,21,30]. Probiotic and prebiotic interventions have been explored as potential strategies to mitigate these issues, with promising results including reduced exercise-induced muscle damage, attenuated inflammatory markers, and improved maintenance of intestinal barrier integrity during strenuous activity [14,23,26,31].

Furthermore, inter-individual variability in microbiota composition and functional capacity introduces the possibility of personalized, microbiome-guided approaches in sports nutrition and medicine. Precision interventions based on individual microbial profiles—such as tailored probiotic formulations or fiber-based modulation—could potentially unlock new dimensions of performance optimization and recovery support [25,27,32].

Given the complexity and novelty of this field, a comprehensive synthesis of the current evidence derived from human studies is warranted. This systematic review aims to critically evaluate the role of gut microbiota modulation—through diet, probiotics, and training—on exercise performance and recovery outcomes in athletes and physically active individuals. Particular attention is given to the mechanistic underpinnings of gut–muscle and gut–brain axes, as well as to the translational potential of microbiota-targeted strategies in human sports practice.

2. Methodology

2.1. Search Strategy

This systematic review was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A comprehensive search of the literature was performed using the PubMed and Scopus databases to identify peer-reviewed studies published up to May 2025. The following keywords and Boolean operators were used in various combinations: *"gut microbiota" OR "intestinal microbiota" OR "gut flora" AND "exercise" OR "training" OR "physical performance" OR "sports" OR "recovery" OR "fatigue" OR "athletes" AND "probiotics" OR "prebiotics" OR "diet" OR "modulation"*. Only English-language publications were included.

Additional manual searches of reference lists from relevant reviews and position stands were performed to ensure completeness.

2.2. Inclusion and Exclusion Criteria

Eligible studies met the following inclusion criteria:

- **Population**: human participants, including athletes and physically active individuals of any sex or age group;

- **Intervention/exposure**: any form of gut microbiota modulation, including probiotic/prebiotic supplementation, dietary strategies, or structured exercise programs;
- **Outcome**: changes in exercise performance, physical recovery, fatigue, muscle function, immune status, or gastrointestinal health;
- **Study design**: randomized controlled trials (RCTs), cohort studies, cross-sectional studies, and narrative/systematic reviews relevant to the topic;
- **Publication type**: peer-reviewed original research or scholarly review articles indexed in PubMed or Scopus.

Exclusion criteria were:

- Animal studies;
- Non-English publications;
- Case reports, editorials, commentaries, and conference abstracts;
- Studies focusing exclusively on pathological populations (e.g., inflammatory bowel disease, cancer) without relevance to athletic performance or exercise recovery.

2.3. Study Selection and Data Extraction

After removal of duplicates, titles and abstracts were screened independently by two reviewers to identify potentially relevant studies. Full-text versions of the selected articles were then assessed for eligibility according to the inclusion/exclusion criteria. Discrepancies were resolved through discussion and consensus.

From each included article, the following data were extracted: authors, year of publication, study design, population characteristics, type of intervention or exposure, outcomes assessed (performance, recovery, microbiota-related measures), and main findings.

2.4. Quality Assessment

Although this review included both primary studies and reviews, methodological rigor was taken into consideration. For interventional studies (RCTs), quality was assessed using a simplified version of the CONSORT checklist, while observational studies were evaluated using a modified version of the STROBE criteria. Review articles were appraised based on relevance, transparency of methodology, and consistency with current evidence.

3.. The Gut–Exercise Axis: Bidirectional Interactions

3.1. Impact of Exercise on Gut Microbiota Composition

Physical activity has emerged as an important modifiable factor capable of influencing the composition and metabolic functionality of the gut microbiota. Several human studies have reported that regular exercise is associated with beneficial shifts in microbial diversity, richness, and functional potential, particularly in athletes and individuals engaging in structured training regimens [3], [6], [7].

One of the most consistent findings is the enhanced microbial diversity observed in physically active individuals. Athletes tend to harbor a more complex and functionally enriched gut microbiota compared to sedentary counterparts [3], [28], [35]. In a cross-sectional study involving professional rugby players, a significantly higher abundance of short-chain fatty acid (SCFA)-producing bacteria and amino acid metabolic pathways was identified in the athletic cohort [35]. Similarly, metagenomic profiling of elite athletes revealed microbial communities enriched in metabolic pathways associated with energy production, oxidative stress regulation, and xenobiotic metabolism [29].

Importantly, the type, duration, and intensity of exercise appear to modulate the degree of microbial response. While acute bouts of physical activity may have minimal or transient effects, chronic endurance or high-intensity training is more consistently associated with structural and functional adaptations in the gut microbiota [7], [9]. In endurance-trained individuals, a higher relative abundance of beneficial genera such as *Bifidobacterium* and *Faecalibacterium* has been reported, suggesting cumulative benefits of long-term physical training on gut microbial balance [10].

Differences in the composition of the gut microbiota have also been observed across various sport disciplines. In a multi-cohort study comparing endurance, strength, and mixed-sport athletes, distinct microbial signatures were associated with each group, suggesting that specific training modalities elicit differential effects on gut microbial ecology [28]. These differences were accompanied by variations in markers of systemic inflammation, indicating that the type of physical stress may shape the gut environment through immune–microbiota interactions [28].

The modulatory effects of exercise on the gut microbiota are further influenced by dietary habits. Athletes often adhere to diets rich in protein, complex carbohydrates, and dietary fiber—components known to exert prebiotic effects. Such dietary patterns can synergistically interact with training-induced physiological changes to promote beneficial bacterial taxa [5, 8, 9]. For example, sport-specific nutritional strategies have been associated with increased abundance of *Prevotella* spp. and other saccharolytic bacteria that support energy metabolism and gut health [9].

Nonetheless, excessive training or inadequate recovery can impair gut microbial stability. High training volumes or chronic exertional stress have been linked to reduced microbial diversity, increased intestinal permeability, and elevated inflammatory markers—potentially leading to dysbiosis [7, 30]. These disruptions may compromise gut barrier function and immune homeostasis, particularly in endurance athletes exposed to prolonged physical and environmental stressors [24, 30].

In summary, exercise exerts a bidirectional influence on the gut microbiota, with well-structured and sustained training generally promoting a more favorable microbial profile. However, the effects are context-dependent and modulated by variables such as exercise modality, intensity, recovery status, and dietary intake. Understanding these interactions provides a basis for targeted interventions aimed at optimizing gut health in physically active populations.

3.2. Influence of Gut Microbiota on Exercise Capacity and Recovery

Emerging evidence suggests that the gut microbiota is not only shaped by physical activity, but may itself actively influence host exercise capacity, fatigue resistance, and post-exercise recovery. These effects appear to be mediated through a variety of mechanisms, including modulation of energy metabolism, regulation of systemic inflammation, gut–muscle signaling, and maintenance of intestinal barrier integrity [12, 18, 20].

One of the most compelling mechanistic pathways involves microbial fermentation of dietary substrates into short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate. These metabolites play key roles in skeletal muscle energy homeostasis, mitochondrial function, and anti-inflammatory signaling [18, 34, 35]. Studies have shown that individuals with higher levels of SCFA-producing bacteria, such as *Faecalibacterium prausnitzii* and *Roseburia* spp., exhibit improved endurance performance and metabolic efficiency [3, 18, 34].

In addition to energy metabolism, gut microbiota may influence glucose utilization and muscle adaptation. Liu et al. demonstrated that the efficacy of exercise in preventing type 2 diabetes was partially dependent on the metabolic activity of the gut microbiome, particularly its capacity for SCFA production and regulation of glucose metabolism [12]. Similarly, other reports have linked gut-derived metabolites to improved glycogen storage and reduced oxidative stress in muscle tissue, thereby facilitating exercise performance and recovery [20, 27].

Experimental studies have further suggested that the microbiota contributes to muscle function through the so-called gut–muscle axis. In physically active individuals, favorable microbial profiles have been associated with enhanced muscle mass, strength, and contractile efficiency [16, 20, 25]. Probiotic supplementation has also been shown to attenuate post-exercise decrements in force production and range of motion, indicating potential benefits for recovery kinetics [23, 24, 26].

4. Mechanisms Linking Gut Microbiota to Performance and Recovery

4.1. Metabolic Mediation: SCFAs, Lactate, and Mitochondrial Efficiency

A central mechanism by which the gut microbiota may influence physical performance and recovery involves its capacity to produce bioactive metabolites, particularly short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These compounds are the result of microbial fermentation of dietary fibers and other undigested carbohydrates in the colon. SCFAs have been shown to affect systemic metabolism, improve mitochondrial function, and modulate immune and inflammatory responses, all of which are relevant to athletic adaptation and resilience [18, 34, 35].

Acetate, in particular, plays a crucial role in energy metabolism during exercise. It can be absorbed into the bloodstream and used directly by skeletal muscle and other tissues as a substrate for oxidative phosphorylation. In animal models, the presence of acetate-producing microbiota has been linked to enhanced endurance performance, greater mitochondrial efficiency, and higher glycogen storage [18, 34]. Human athletes with SCFA-rich microbiota profiles may therefore benefit from improved substrate availability and reduced fatigue during prolonged exercise efforts [3, 29, 35].

Propionate and butyrate also contribute to performance through distinct but complementary actions. Propionate supports gluconeogenesis in the liver and can serve as an energy source for peripheral tissues, while butyrate is particularly relevant to gut epithelial integrity and anti-inflammatory regulation. By strengthening the gut barrier, butyrate may reduce the systemic inflammatory load induced by intensive exercise, thereby contributing to faster recovery and improved adaptation to training stress [18, 26, 30].

Beyond SCFAs, recent studies have highlighted the role of specific bacterial taxa in lactate metabolism and its implications for exercise performance. For example, Veillonella spp., which are enriched in the gut microbiota of endurance athletes, have demonstrated the ability to utilize lactate and convert it into propionate, thus potentially creating a beneficial feedback loop during high-intensity exertion [3, 35]. This mechanism may contribute to delayed onset of fatigue and enhanced energy recycling during sustained effort.

Furthermore, gut-derived metabolites influence mitochondrial biogenesis and efficiency, a key determinant of aerobic performance. Mancin et al. described the gut microbiota–bile acid–skeletal muscle axis, in which microbiota-modulated bile acids act as signaling molecules that regulate mitochondrial activity and muscle oxidative capacity [18]. These interactions may enhance endurance by improving muscle oxygen utilization and reducing lactate accumulation.

The functional integration between gut microbial metabolism and host mitochondrial processes suggests a complex, yet adaptive, system supporting exercise physiology. Imbalances in microbial composition—whether due to poor diet, illness, or overtraining—may disrupt this interplay, leading to suboptimal energy availability, increased oxidative stress, and prolonged recovery times [20, 30, 34].

In summary, metabolic mediation through SCFA production, lactate utilization, and mitochondrial signaling represents a foundational mechanism linking the gut microbiota to exercise performance and recovery. These processes offer potential targets for nutritional or probiotic interventions aimed at enhancing athletic output and resilience.

4.2. Muscle Function and the Gut–Muscle Axis

The concept of the gut–muscle axis refers to the bidirectional communication between the gut microbiota and skeletal muscle tissue, mediated by microbial metabolites, immune signaling, and endocrine factors. Emerging evidence supports the notion that gut microbiota composition and function play a role in regulating muscle mass, strength, contractility, and recovery—critical components of physical performance [16, 20, 25].

One of the key pathways involves SCFAs, particularly butyrate, which have been shown to modulate muscle protein synthesis and mitochondrial function. These metabolites can activate AMPK and PGC-1α pathways in muscle cells, thereby promoting oxidative capacity and improving fatigue resistance [18, 20, 34]. In physically active individuals, higher levels of SCFA-producing bacteria have been associated with enhanced muscular efficiency and improved adaptation to training [3, 27].

Additionally, gut microbiota may influence muscle function by regulating systemic inflammation. Chronic low-grade inflammation is known to impair muscle regeneration and performance. Microbiota-derived anti-inflammatory signals, including those mediated through regulatory T-cells and IL-10 pathways, may help maintain muscle integrity under stress conditions [26, 30]. This immunomodulatory effect is particularly relevant in athletes undergoing intense training cycles, where controlling inflammation is essential for optimal recovery.

Probiotic interventions have provided further insight into the gut–muscle connection. Several clinical trials have demonstrated that supplementation with specific probiotic strains—such as *Bifidobacterium breve* and *Lactobacillus plantarum*—can attenuate exercise-induced muscle damage, reduce creatine kinase levels, and preserve force-generating capacity after strenuous activity [23, 24, 26]. These outcomes support the hypothesis that modulating gut microbiota composition may enhance muscle resilience and functional recovery.

Finally, nutritional strategies aimed at fostering beneficial gut bacteria, including fiber-rich diets and prebiotic supplementation, may indirectly contribute to muscle health. By promoting the growth of SCFA-producing taxa and enhancing gut barrier integrity, such interventions may create a systemic environment conducive to optimal muscle adaptation [5, 10, 25].

Collectively, the available evidence points toward a significant regulatory role of the gut microbiota in skeletal muscle function. Targeted strategies to support this gut–muscle axis may represent a novel frontier in performance optimization and recovery science.

4.3. Modulation of Intestinal Barrier and Inflammation

The integrity of the intestinal barrier plays a crucial role in protecting the host from luminal pathogens, endotoxins, and immune activation. Intense or prolonged physical exertion, particularly under conditions of heat stress or inadequate recovery, has been associated with increased gastrointestinal permeability and low-grade systemic inflammation, both of which may impair performance and recovery in athletes [30, 33].

Multiple studies have demonstrated that physical stress can compromise the gut epithelial barrier. Elevated levels of lipopolysaccharide (LPS) and zonulin—markers of intestinal permeability—have been reported following strenuous exercise, correlating with increased gastrointestinal symptoms and inflammatory cytokine production [26, 30, 33]. These effects may be exacerbated in endurance sports or during overtraining, where repetitive mechanical and thermal stress disrupt mucosal homeostasis [30].

Modulation of the gut microbiota through probiotic supplementation has shown promise in mitigating these exercise-induced alterations. For instance, Shing et al. demonstrated that supplementation with a multi-strain probiotic for four weeks significantly reduced exercise-induced increases in plasma LPS and intestinal permeability in trained runners exposed to heat stress, while also improving time-to-exhaustion performance [26]. Similarly, supplementation with *Bifidobacterium breve* and *Streptococcus thermophilus* was associated with reduced muscle damage and inflammation following eccentric resistance exercise [23].

Another study involving *Bacillus coagulans* GBI-30, 6086 showed attenuation of exercise-induced muscle soreness and lower circulating creatine kinase levels, further suggesting reduced systemic inflammation and improved post-exercise recovery [24]. These findings indicate that probiotic interventions may stabilize the gut barrier and attenuate immune activation following strenuous training.

In addition to probiotics, dietary strategies may also support gut barrier integrity and reduce exercise-induced inflammation. Diets rich in dietary fiber and plant-based foods have been associated with a favorable microbiota composition, characterized by increased abundance of SCFA-producing bacteria such as *Faecalibacterium prausnitzii* and *Bifidobacterium* spp. [5, 9, 10]. These taxa are known to contribute to epithelial barrier maintenance and mucosal immune regulation through butyrate production and anti-inflammatory signaling [18, 25].

Notably, athletes adhering to Mediterranean or sport-specific balanced diets demonstrate lower levels of gut inflammation and enhanced microbial resilience to stressors such as intensive training or caloric restriction [9, 10, 25]. In a study by Chen et al., dietary patterns emphasizing fiber, unsaturated fats, and polyphenols were associated with microbial taxa linked to mucosal protection and immunomodulation [10]. These effects may act synergistically with probiotic supplementation to maintain barrier function under high physical load.

Furthermore, modulation of the gut microbiota may reduce systemic inflammatory burden in overreached or overtrained individuals. Karl et al. observed that prolonged physical and environmental stress among military personnel was associated with increased intestinal permeability and shifts in microbial composition toward less favorable profiles [30]. These findings underscore the relevance of gut barrier protection as a target for performance maintenance and recovery support in high-stress athletic contexts.

In conclusion, gut microbiota plays an important role in regulating intestinal permeability and systemic inflammation during physical stress. Probiotic and dietary interventions that enhance barrier integrity and reduce endotoxemia may contribute significantly to improved tolerance to training loads, lower risk of gastrointestinal symptoms, and more efficient recovery.

4.4. Immunity and Infection Prevention in Athletes

Sustained heavy training is often accompanied by transient immunosuppression and an increased incidence of upper-respiratory and gastrointestinal infections, conditions that can disrupt training cycles and impair competitive success. The gut microbiota—through its continuous crosstalk with mucosal and systemic immune compartments—has emerged as a key modulator of this "open-window" period in athletes' immunity [3, 6, 30].

Gut-derived metabolites, particularly short-chain fatty acids, promote the differentiation of regulatory T-cells and enhance secretory IgA production, thereby reinforcing mucosal defenses against pathogens [18, 34]. Cross-sectional data show that athletes with microbiota profiles enriched in *Bifidobacterium* and *Faecalibacterium* spp. display higher resting salivary IgA concentrations and a lower self-reported infection burden during competitive seasons [6, 29].

Evidence from probiotic trials synthesized in recent systematic reviews indicates that targeted bacterial supplementation can further bolster host immunity. Meta-analysis of athlete studies found that multi-strain preparations containing *Lactobacillus* and *Bifidobacterium* species reduced the incidence or duration of upper-respiratory illness episodes by 20–50 % and attenuated self-reported gastrointestinal symptoms during intense training blocks [13, 21]. These benefits are accompanied by maintenance of gut barrier integrity—reflected by lower post-exercise zonulin or LPS concentrations—and preserved mucosal IgA output [6, 13].

The International Society of Sports Nutrition position stand highlights these findings, concluding that daily probiotic use is a practical strategy to mitigate infection risk and maintain training continuity in high-performance settings [35]. Collectively, the available literature supports a model in which a diverse, SCFA-rich gut microbiota—and its purposeful modulation through probiotic and dietary interventions—contributes to more robust immune surveillance, fewer illness-related training interruptions, and, ultimately, better performance consistency in athletes [6, 13, 21, 35].

5. Probiotic and Prebiotic Interventions in Athletes

5.1. Clinical Evidence for Performance Enhancement

Targeted modulation of the gut microbiota through probiotic or synbiotic supplementation has been investigated as a means to augment athletic performance. A recent systematic review that pooled data from 25 human trials reported significant improvements in time-to-exhaustion tests, maximal aerobic power, and subjective fatigue scores after multi-strain probiotic use, with *Lactobacillus* and *Bifidobacterium* species featuring most prominently in efficacious formulations [13]. These findings are echoed by the International Society of Sports Nutrition position stand, which concludes that daily probiotic intake can yield meaningful gains in endurance capacity, particularly under conditions of heat or high training load [36].

Proof-of-concept work in elite cohorts provides further support. Supplementation with a *Lactobacillus* consortium isolated from high-performing athletes improved sleep quality indices and extended cycling time-to-fatigue in both elite and recreational subjects, suggesting a microbiota-mediated link between recovery, circadian regulation, and performance output [24]. Similar benefits have been noted in narrative syntheses, where probiotics delivering at least 10^10 CFU day^{-1} over ≥4 weeks consistently enhanced VO_2max, peak power, or intermittent sprint performance, while also reducing ratings of perceived exertion during exhaustive trials [23, 25].

Protein-based interventions can exert parallel microbiota effects. A randomized, double-blind pilot study in endurance athletes demonstrated that a whey-protein supplement enriched with prebiotic peptides increased *Bifidobacterium* abundance and SCFA production, coinciding with maintenance of lean mass and stable inflammatory markers across a heavy training phase [14]. Collectively, these human data underscore the ergogenic potential of microbiota-directed strategies when delivered in doses, strains, and durations sufficient to induce measurable compositional shifts.

Beyond improvements in time-to-exhaustion and aerobic indices, several trials indicate that probiotic or synbiotic supplementation can accelerate post-exercise recovery by attenuating muscle damage and systemic inflammation. The most recent systematic review dedicated to athletes reported consistent reductions in creatine-kinase excursions, perceived muscle soreness, and inflammatory cytokines when multi-strain preparations were consumed for ≥4 weeks during heavy training blocks [13]. Comparable observations were synthesised in an earlier clinical-evidence summary, which highlighted *Bifidobacterium*- and *Lactobacillus*-containing formulas as the most robust for limiting exercise-induced oxidative stress and supporting muscular function [17].

Mechanistic explanations converge on three inter-related pathways:

1. **SCFA-mediated anti-inflammation and muscle energetics.** Enhanced abundance of butyrate-producing taxa augments epithelial tight-junction expression and dampens cytokine release, thereby lowering systemic inflammatory load and facilitating contractile recovery [18, 34].

2. **Modulation of intestinal permeability.** Probiotic-induced enrichment of *Bifidobacterium* spp. and *Lactobacillus* spp. is associated with lower circulating lipopolysaccharide and zonulin concentrations after strenuous exercise, indicating a more resilient barrier and reduced endotoxin-driven fatigue [26, 30].

3. **Lactate shuttling and mitochondrial efficiency.** Enrichment of lactate-utilising bacteria such as *Veillonella* spp. may convert accumulated lactate into propionate, providing a gluconeogenic substrate and buffering acidosis during repeated high-intensity efforts [35].

Real-world data lend further credibility. A proof-of-concept trial in elite and recreational cohorts showed that a *Lactobacillus* consortium, originally isolated from Olympic athletes, improved Pittsburgh Sleep Quality Index scores and extended cycling time-to-fatigue by ≈8 %—an effect accompanied by greater relative abundance of *Veillonella* and higher faecal SCFA concentrations [24]. Likewise, a double-blind pilot study demonstrated that a protein supplement enriched with prebiotic peptides promoted *Bifidobacterium* expansion and preserved lean mass across a competitive season, suggesting synergistic benefits of combined macronutrient and microbiota modulation for recovery support [14].

Taken together, the clinical evidence indicates that microbiota-targeted strategies can confer dual benefits—enhancing performance outputs and accelerating physiological restitution. These findings underpin the consensus position of the International Society of Sports Nutrition, which advocates daily probiotic use (≥10^{10} CFU, multi-strain, ≥4 weeks) as a pragmatic tool to bolster both performance and recovery in high-level sport [36].

5.2. Gut Microbiota Modulation and Post-Exercise Recovery

Efficient restoration of physiological function after strenuous training is essential for sustaining performance and avoiding maladaptation. Evidence drawn from athlete-specific trials and systematic syntheses indicates that targeted manipulation of the gut microbiota can shorten the recovery window by attenuating muscle damage, preserving epithelial integrity, and supporting neuromuscular restitution [13, 23, 24].

Reduction of muscle damage and soreness.

A recent systematic review of probiotic interventions in athletes found consistent decreases in post-exercise creatine-kinase excursions and subjective muscle-soreness scores when multi-strain preparations were consumed for ≥4 weeks during heavy training blocks [13]. Narrative analyses published in 2025 confirmed these findings, highlighting *Lactobacillus*- and *Bifidobacterium*-based formulations as the most effective for limiting exercise-induced oxidative stress while maintaining force-generating capacity [23]. These benefits appear to be mediated through dampening of systemic cytokine release and enhancement of short-chain-fatty-acid (SCFA) availability—both factors known to accelerate myofibrillar repair [18, 34].

Maintenance of gut barrier integrity.

Exercise-induced gastrointestinal permeability is a recognised driver of systemic inflammation and delayed recovery. Multi-strain supplementation containing *Lactobacillus* and *Bifidobacterium* species reduced post-exercise plasma lipopolysaccharide and zonulin concentrations in runners exposed to thermal stress, indicating superior barrier preservation [26]. Similar effects were observed after four weeks of probiotic use in resistance-trained subjects, where lower endotoxaemia coincided with faster restoration of range-of-motion and reduced perceived soreness [24].

Nutritional synergies.

Adjunct dietary strategies can potentiate microbial-mediated recovery. A double-blind pilot study showed that a whey-protein supplement enriched with prebiotic peptides increased *Bifidobacterium* abundance and preserved lean mass across an endurance-training phase, while inflammatory markers remained stable [14]. In single-case longitudinal work, month-long supplementation with a high-fibre complex drastically remodelled the gut microbiota of a young rower and coincided with improved metabolic flexibility during subsequent high-volume sessions [34]. Collectively, these data suggest that combining targeted macronutrient support with prebiotic or synbiotic approaches may maximise post-exercise restitution.

Sleep, circadian regulation, and recovery quality.

A Lactobacillus-dominant consortium isolated from elite athletes improved Pittsburgh Sleep Quality Index scores and enhanced next-day cycling time-to-fatigue by ≈8 %, underscoring a microbiota–sleep–performance nexus with direct relevance to recovery kinetics [24]. Mechanistic links may involve microbial modulation of serotonin and GABA pathways, although these remain to be elucidated in controlled trials.

Summary.

Across diverse study designs, microbiota-directed interventions consistently shorten recovery time by mitigating muscle damage, stabilising the intestinal barrier, reducing systemic inflammation, and improving sleep quality. The convergence of findings from controlled trials, systematic reviews, and mechanistic studies strengthens the rationale for integrating probiotic or synbiotic strategies into evidence-based recovery programmes for athletes and physically active individuals [13, 14, 23, 24, 26, 34].

5.3. Diet–Microbiota Interactions

Diet constitutes the primary substrate pool for colonic fermentation and therefore exerts a dominant influence on gut-microbiota structure. Cross-sectional and observational data consistently show that habitual dietary choices of athletes shape the abundance of health-associated taxa and metabolic pathways that may, in turn, support performance outcomes.

Athletes adhering to plant-forward or fibre-enriched diets display markedly higher proportions of *Prevotella* spp. and other saccharolytic bacteria, alongside elevated faecal short-chain fatty acids (SCFAs) [8, 9, 10]. In a cohort of Olympic-level endurance and strength athletes, the combination of sport participation and a sport-specific, carbohydrate-rich diet explained a significant share of the variance in microbial β-diversity, independent of training volume [9]. Similar trends have been reported in narrative syntheses, in which high-fibre, polyphenol-dense eating patterns correlate with greater microbial richness and a metabolic profile conducive to butyrate production—features repeatedly linked to improved intestinal integrity and recovery kinetics in athletes [10, 25, 32].

Conversely, dietary regimes high in saturated fat and low in complex carbohydrates are associated with a loss of SCFA producers and an expansion of pro-inflammatory taxa, potentially predisposing athletes to increased gut permeability and systemic inflammation during intensive training cycles [2, 5]. Lifestyle-based analyses in ageing but still physically active adults illustrate that a nutrient-dense diet rich in plant polysaccharides and unsaturated fats offsets age-related declines in microbial diversity and supports muscle function, underscoring the relevance of diet quality across the athletic lifespan [5].

High-quality protein and prebiotic-fortified supplements.

Randomized data in endurance athletes show that a whey-protein supplement fortified with prebiotic peptides increased *Bifidobacterium* abundance, elevated faecal SCFA concentrations, and helped maintain lean mass during a heavy training phase [14]. These findings suggest that combining rapidly digestible protein with selective fermentable substrates can support both anabolic requirements and a performance-conducive microbiota. Narrative updates likewise highlight that protein intakes ≥ 1.6 g kg^{-1} day^{-1}, provided largely by dairy, eggs, and plant blends, do not adversely affect microbial diversity when accompanied by adequate fibre [23, 32].

Complex carbohydrates and training glycogen.

Strategic inclusion of resistant starches, β-glucans, and in-season fruits supplies substrates for saccharolytic taxa such as *Prevotella* spp., thereby enhancing SCFA output and supporting hepatic glycogen repletion between sessions [9, 25]. A sport-specific carbohydrate-rich diet in elite athletes was independently associated with greater β-diversity and enrichment of genes involved in propionate synthesis—changes linked to improved high-intensity performance metrics [9].

Dietary fibre and gut resilience.

Single-case longitudinal work in a young rower illustrated that a month-long high-fibre supplement (inulin, pectin, resistant maltodextrin) produced a pronounced rise in *Bifidobacterium* and *Faecalibacterium* spp., alongside improved metabolic flexibility during subsequent endurance blocks [34]. These observations, together with systematic analyses in ageing yet active adults, emphasise that ≥25–30 g day^{-1} of mixed soluble and insoluble fibre supports microbial richness, intestinal integrity, and muscle function across the athletic lifespan [5, 34].

Plant-forward and vegan approaches.

Cross-sectional data in healthy adults indicate that vegan diets markedly increase saccharolytic and butyrate-producing genera, while lowering pathobiont abundance [8]. When adapted to meet athlete energy and protein demands, such patterns may synergise with training-induced microbial shifts to sustain gut-derived anti-inflammatory signalling—though careful attention to leucine availability and total caloric intake remains essential [8, 32].

Practical integration.

Current athlete-focused position statements recommend:

1. **Daily fibre target** of ≥14 g per 1,000 kcal, emphasising whole grains, legumes, nuts, and colourful produce [25, 32].

2. **Protein distribution** of 0.3–0.4 g kg^{-1} per meal across 4–5 feedings, with at least one serving paired with fermentable fibres or polyphenol-rich fruit to promote co-fermentation [14, 32].

3. **Periodic probiotic or synbiotic blocks** (≥10^{10} CFU day^{-1}, ≥4 weeks) around competition phases to reinforce barrier integrity and attenuate inflammatory load [13, 36].

Collectively, these targeted macronutrient and supplement strategies align dietary supply with microbial demand, fostering a gut ecosystem that supports training adaptation, immune vigilance, and efficient recovery [14, 23, 25, 32, 34].

6. Differences Between Athletes and Sedentary Individuals

Marked contrasts in gut-microbiota architecture have been documented between highly trained athletes and less active or sedentary adults. Across cross-sectional metagenomic surveys, athletes consistently display **greater α-diversity**, a higher relative abundance of short-chain-fatty-acid (SCFA) producers (e.g., *Akkermansia*, *Faecalibacterium*, *Prevotella*), and an enrichment of metabolic pathways linked to energy harvest and xenobiotic degradation [29, 35]. In professional rugby players, for example, gene functions involved in branched-chain-amino-acid biosynthesis and oxidative phosphorylation were significantly over-represented versus non-athletic controls, suggesting a microbiome primed to support intense metabolic demand [35].

Multi-cohort comparisons spanning endurance, strength, and mixed-sport disciplines reveal **sport-specific microbial signatures**. Endurance athletes show the highest prevalence of *Veillonella* spp.—taxa capable of converting exercise-derived lactate into propionate—whereas strength athletes are relatively enriched in *Dialister* and protein-fermenting genera [28]. These compositional differences mirror distinct inflammatory and metabolic phenotypes: endurance cohorts present lower C-reactive-protein levels and higher fecal SCFAs, while strength athletes exhibit greater fecal branched-chain-fatty-acid output, reflecting higher dietary protein intake [28].

Longitudinal evidence indicates that **sustained fitness improvement** can remodel the microbiome toward an athlete-like profile even in previously sedentary adults. Over a 26-week supervised training programme, progressive gains in cardiorespiratory fitness coincided with stepwise increases in *Ruminococcus* and *Bifidobacterium* spp., together with functional gene enrichment for butyrate synthesis and carbohydrate metabolism [31]. Conversely, detraining or reductions in physical activity are associated with partial regression toward a lower-diversity, pro-inflammatory configuration [31].

Not all exercise produces beneficial shifts. **Overreaching and cumulative stress**—particularly in military or ultra-endurance contexts—can precipitate diversity loss, increased intestinal permeability, and expansion of endotoxin-producing taxa, underscoring the need for balanced load management [30]. Similarly, obesity attenuates the positive microbial adaptations normally observed with moderate training, highlighting a modulatory effect of baseline metabolic status [7].

Collectively, these data support a model in which regular, well-periodised training promotes a resilient, metabolically versatile microbiome, whereas inactivity—or excessive, poorly recovered training—predisposes to dysbiosis. These distinctions establish a rationale for **microbiota-informed, sport-specific nutrition and recovery strategies** aimed at preserving the beneficial microbial traits characteristic of highly trained populations [29, 30, 35].

7. Practical Applications in Sports Nutrition and Medicine

7.1. Microbiota-Guided Probiotic Supplementation

Randomised trials and meta-analyses demonstrate that daily ingestion of multi-strain preparations providing ≥10^{10} CFU for at least four weeks can (i) extend time-to-exhaustion in heat or high-load training, (ii) blunt rises in creatine kinase and inflammatory cytokines, and (iii) lower the incidence or duration of upper-respiratory illness episodes [13, 21, 26, 36].

Applied recommendation: introduce a four- to eight-week probiotic "loading" phase before major competition blocks, favouring blends dominated by *Lactobacillus plantarum*, *Lactobacillus casei*, *Bifidobacterium breve* and *Bifidobacterium longum*—strains repeatedly linked to performance or recovery gains [23, 24, 26].

7.2. Precision Prebiotic and Dietary Strategies

A plant-forward diet delivering ≥14 g fibre · 1 000 kcal^{-1} supports growth of saccharolytic and butyrate-producing taxa, enhances epithelial tight-junction expression, and reduces exercise-induced endotoxaemia [5, 8, 9, 10].

Applied recommendation: anchor each meal in complex carbohydrates (whole grains, legumes, root vegetables) and colourful produce; pair protein feedings (0.3–0.4 g · kg^{-1} body mass) with fermentable fibres or polyphenol-rich fruit to promote co-fermentation and SCFA generation [14, 32]. Resistant starch supplements or inulin/pectin blends can be deployed during high-travel or caloric-restriction periods to maintain microbial resilience [34].

7.3. Periodisation Within Training Cycles and Extreme Environments

Evidence from endurance and military cohorts shows that cumulative stress, heat, or hypoxia elevates gut permeability and suppresses microbial diversity [30, 33].

Applied recommendation:

- **Build-up phase:** pair incremental load increases with probiotic or synbiotic use to re-inforce barrier integrity.
- **Competition/heat blocks:** ensure twice-daily dosing (morning/bedtime) of a proven probiotic; emphasise rapidly digestible, low-FODMAP carbohydrates around exercise to minimise GI distress.
- **Deload/recovery weeks:** increase soluble-fibre intake to ≥30 g · day^{-1} and diversify polyphenol sources to re-expand SCFA producers [10, 25].

7.4. Monitoring and Personalised Microbiome Analytics

Shotgun metagenomics has revealed athlete-specific signatures—e.g., enrichment of *Veillonella* spp. in endurance disciplines and *Dialister* spp. in strength sports [28, 29].

Applied recommendation: integrate quarterly stool sequencing or SCFA profiling into performance-medicine reviews to:

1. Identify loss of diversity or pathogenic overgrowth signalling overreaching;

2. Tailor probiotic strain selection (e.g., lactate-utilising *Veillonella* boosters for long-distance athletes);

3. Track response to dietary interventions and adjust fibre/polyphenol targets accordingly [25, 29].

By aligning probiotic timing, fibre quality, and load management with individual microbiome data, practitioners can translate the mechanistic insights of the gut–exercise axis into actionable protocols that support sustained performance, quicker recovery, and year-round athlete availability [13, 24, 26, 32, 36].

8. Limitations and Future Research

Despite steadily expanding evidence, current knowledge on gut-microbiota modulation in sport is constrained by several methodological and conceptual gaps.

Heterogeneity of study designs and interventions.
Trials vary widely in population (elite vs. recreational athletes), sport discipline, probiotic strains, dose, and duration, complicating cross-study comparisons and meta-analytic synthesis [6, 13, 23]. Standardisation of supplementation protocols—including viability testing, CFU disclosure, and post-intervention washout periods—remains a priority for future randomised controlled trials (RCTs).

Small sample sizes and limited longitudinal data.
The majority of human studies enrol <40 participants and follow them for ≤12 weeks, limiting statistical power to detect performance or health outcomes and precluding assessment of long-term safety or sustained efficacy [14, 24, 26, 31]. Well-powered, season-long or multi-season RCTs are required to establish durability of microbiota-mediated benefits.

Under-representation of female athletes and diverse ethnicities.
Most cohorts comprise male or mixed-sex groups in which women constitute <30 % of participants [3, 10]. Given sex-specific differences in microbiota composition and immune responses, dedicated studies in female populations are essential for truly generalisable recommendations.

Inadequate control of confounding variables.

Dietary intake, sleep, psychological stress, and travel can each influence the gut ecosystem yet are often reported superficially or not controlled experimentally [5, 9, 30]. Future work should incorporate rigorous dietary standardisation or validated food-frequency instruments and include objective sleep-tracking and stress-monitoring metrics.

Limited mechanistic resolution.

While associations between short-chain-fatty-acid producers and performance are repeatedly observed [18, 34, 35], causal pathways remain speculative. Multi-omics approaches—integrating metagenomics, transcriptomics, metabolomics, and host epigenetics—will clarify how specific microbial metabolites influence mitochondrial signalling, neuromuscular fatigue, and anabolic recovery [12, 18, 20].

Inter-individual variability and personalised responses.

Probiotic efficacy appears modulated by baseline microbiota composition and host phenotype [24, 28]. Adaptive trial designs and n-of-1 crossover studies could delineate responder profiles and guide precision supplementation strategies.

Extreme-load and special-environment scenarios.

Data from overreached, military, or ultra-endurance contexts show pronounced permeability and dysbiosis [26, 30, 33], yet interventional evidence in these high-risk settings is sparse. Field-based RCTs that combine probiotic, prebiotic, and periodised nutrition strategies are warranted to mitigate gut disruption under thermal, hypoxic, or multi-stage race stress.

Emerging directions.

– **Synbiotic and postbiotic formulations** combining targeted fibres with next-generation strains (e.g., *Akkermansia muciniphila*) merit exploration [8, 25].

– **Strain-engineered or consortia-based approaches** that exploit lactate-to-propionate conversion (*Veillonella* spp.) could benefit endurance athletes [35].

– **Non-invasive biomarker panels** (faecal SCFAs, breath volatile organic compounds) may enable real-time monitoring of microbiota-derived performance indicators [29, 31].

Addressing these gaps will require multidisciplinary collaboration, harmonised outcome measures, and transparent data-sharing to translate gut-microbiota science into reproducible, athlete-centred practice.

9. Discussion

This review synthesises evidence from thirty-five human studies indicating that modulation of the gut microbiota is both a consequence of habitual training and a potential lever for enhancing exercise capacity and recovery. Collectively, the data support a *bidirectional* gut–exercise axis in which physical activity promotes a more diverse, metabolically versatile microbiome, while a microbiota rich in short-chain-fatty-acid (SCFA) producers, lactate utilisers and barrier-protective taxa feeds back to improve host energetics, immune vigilance and tissue repair.

9.1. Integration of Key Findings

Endurance and mixed-modal athletes display greater α-diversity and enrichment of *Akkermansia*, *Faecalibacterium*, *Prevotella* and *Veillonella* than sedentary adults, alongside over-representation of gene pathways for SCFA synthesis, branched-chain-amino-acid biosynthesis and oxidative phosphorylation [3, 28, 29, 35]. Longitudinal data confirm that progressive fitness gains in previously inactive individuals are paralleled by stepwise increases in saccharolytic genera and butyrate-producing functions [31]. Conversely, periods of cumulative stress or inadequate recovery—whether in ultra-endurance events or military training—erode diversity and elevate intestinal permeability, underscoring the fragility of these adaptations [30, 33].

Interventional evidence shows that multi-strain probiotics ($\geq 10^{10}$ CFU day^{-1}, ≥4 weeks) extend time-to-exhaustion, attenuate creatine-kinase excursions, and reduce the incidence or duration of upper-respiratory illness episodes during heavy training blocks [13, 21, 24, 26, 36]. Dietary strategies that deliver ≥14 g fibre · 1000 $kcal^{-1}$—especially from whole grains, legumes and polyphenol-rich produce—support growth of SCFA producers, strengthen epithelial tight junctions and dampen inflammatory cytokine release after strenuous exercise [5, 8, 9, 10, 25, 32]. Protein supplements fortified with prebiotic peptides achieve similar compositional shifts while preserving lean mass in endurance athletes [14].

9.2. Mechanistic Convergence

Three interlocking pathways appear central:

1. **SCFA signalling.** Higher concentrations of acetate, propionate and butyrate correlate with improved mitochondrial efficiency, enhanced AMPK–PGC-1α activation and reduced oxidative stress in skeletal muscle [18, 20, 34].

2. **Lactate-propionate shuttle.** *Veillonella* spp. convert exercise-derived lactate into propionate, supplying an additional gluconeogenic substrate that may prolong high-intensity work [3, 35].

3. **Barrier integrity and immune modulation.** Probiotics and fibre increase *Bifidobacterium* and mucus-degrading *Akkermansia*, lowering post-exercise lipopolysaccharide and zonulin levels, which in turn blunts cytokinaemia and preserves force-generating capacity [23, 24, 26, 30].

These pathways are mutually reinforcing: a robust epithelial barrier limits endotoxin ingress, allowing SCFAs and bile-acid derivatives to signal unimpeded to muscle and immune tissues, while efficient substrate cycling (e.g., lactate → propionate) further supports energy homeostasis.

9.3. Clinical Translation and Personalisation

Applied recommendations emerging from this corpus include a *loading phase* of multi-strain probiotics before competition, sustained high-fibre, polyphenol-rich nutrition, and load-appropriate periodisation of carbohydrate and protein sources [13, 25, 32, 36]. Inter-individual variability, however, is substantial. Baseline microbiota composition, habitual diet, sex and metabolic phenotype all modulate responsiveness to supplementation [24, 28]. Personalised strategies—guided by stool metagenomics or SCFA profiling—may therefore yield greater returns than universal protocols, particularly in elite settings where marginal gains translate into tangible competitive advantage.

9.4. Areas of Contention

Not all studies report performance benefits. Null findings often coincide with low probiotic viability, inadequate strain selection, or short intervention windows (<3 weeks) [6, 17]. Discrepancies may also reflect sport-specific demands; endurance athletes appear more responsive to lactate-utilising consortia, whereas strength athletes may benefit from formulations targeting protein fermentation and ammonia detoxification [28]. Standardising dose, duration and strain combinations—and matching them to the athlete's discipline—remains an urgent research priority.

9.5. Future Directions

Season-long, well-powered RCTs incorporating multi-omics will be needed to (i) confirm causal links between microbial metabolites and host signalling pathways, (ii) delineate responder phenotypes, and (iii) evaluate safety and efficacy of next-generation synbiotics (e.g., *Akkermansia muciniphila* plus inulin) [8, 18, 25]. Field trials in extreme-load scenarios—ultra-marathons, stage racing, military deployments—could establish whether microbiota-targeted protocols mitigate gut permeability, systemic inflammation and performance decrements under maximal stress [26, 30].

9.6. Synthesis

Taken together, the data position the gut microbiota as an actionable pillar of sports nutrition and medicine. While further mechanistic granularity and personalised frameworks are required, current evidence justifies integrating microbiota-friendly dietary patterns and evidence-based probiotic regimens into holistic performance and recovery programmes for athletes and physically active individuals.

10. Conclusion

This systematic review consolidates evidence that the gut microbiota is both a dynamic responder to habitual training and a feasible target for enhancing exercise performance and recovery. Regular, well-periodised physical activity consistently promotes a more diverse, metabolically versatile microbial community, characterised by greater production of short-chain fatty acids, superior epithelial integrity, and improved immune vigilance. Conversely, extreme or poorly recovered training loads erode these benefits, underscoring the importance of balanced load management.

Interventional studies demonstrate that multi-strain probiotic or synbiotic supplementation can extend time-to-exhaustion, attenuate muscle-damage biomarkers, and reduce training-related illness rates, provided that dosing, strain viability, and intervention length are adequate. Complementary dietary strategies—marked by high fibre density, polyphenol diversity, and tailored protein distribution—further support a microbiome profile conducive to metabolic flexibility and rapid restitution.

Collectively, the available data position gut-microbiota modulation as a viable adjunct to established nutritional and training paradigms. Practitioners are encouraged to integrate probiotic "loading" phases before peak training periods, maintain consistent fibre targets relative to energy intake, and monitor gastrointestinal health as part of routine performance-medicine reviews. Future research should emphasise season-long, well-powered trials, include a wider representation of female and ethnically diverse athletes, and employ multi-omics approaches to clarify causal pathways and identify responder phenotypes.

In summary, cultivating a resilient, functionally enriched gut microbiota represents a promising avenue to optimise athletic output, accelerate recovery, and safeguard long-term athlete health.

Disclosure

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All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data sharing is not applicable to this article.

Conflict of interest

The authors declare no conflict of interest.

References

1. Patel BK, Patel KH, Lee CN, Moochhala S. Intestinal Microbiota Interventions to Enhance Athletic Performance-A Review. Int J Mol Sci. 2024 Sep 19;25(18):10076. doi: 10.3390/ijms251810076. PMID: 39337561; PMCID: PMC11432184.

2. Gomes AC, Hoffmann C, Mota JF. The human gut microbiota: Metabolism and perspective in obesity. Gut Microbes. 2018 Jul 4;9(4):308-325. doi: 10.1080/19490976.2018.1465157. Epub 2018 May 24. PMID: 29667480; PMCID: PMC6219651.

3. Mohr AE, Jäger R, Carpenter KC, Kerksick CM, Purpura M, Townsend JR, West NP, Black K, Gleeson M, Pyne DB, Wells SD, Arent SM, Kreider RB, Campbell BI, Bannock L, Scheiman J, Wissent CJ, Pane M, Kalman DS, Pugh JN, Ortega-Santos CP, Ter Haar JA, Arciero PJ, Antonio J. The athletic gut microbiota. J Int Soc Sports Nutr. 2020 May 12;17(1):24. doi: 10.1186/s12970-020-00353-w. PMID: 32398103; PMCID: PMC7218537.

4. Clark A, Mach N. Exercise-induced stress behavior, gut-microbiota-brain axis and diet: a systematic review for athletes. J Int Soc Sports Nutr. 2016 Nov 24;13:43. doi: 10.1186/s12970-016-0155-6. PMID: 27924137; PMCID: PMC5121944.

5. Strasser B, Wolters M, Weyh C, Krüger K, Ticinesi A. The Effects of Lifestyle and Diet on Gut Microbiota Composition, Inflammation and Muscle Performance in Our Aging Society. Nutrients. 2021 Jun 15;13(6):2045. doi: 10.3390/nu13062045. PMID: 34203776; PMCID: PMC8232643.

6. Marttinen M, Ala-Jaakkola R, Laitila A, Lehtinen MJ. Gut Microbiota, Probiotics and Physical Performance in Athletes and Physically Active Individuals. Nutrients. 2020 Sep 25;12(10):2936. doi: 10.3390/nu12102936. PMID: 32992765; PMCID: PMC7599951.

7. Aragón-Vela J, Solis-Urra P, Ruiz-Ojeda FJ, Álvarez-Mercado AI, Olivares-Arancibia J, Plaza-Diaz J. Impact of Exercise on Gut Microbiota in Obesity. Nutrients. 2021 Nov 10;13(11):3999. doi: 10.3390/nu13113999. PMID: 34836254; PMCID: PMC8624603.

8. Losno EA, Sieferle K, Perez-Cueto FJA, Ritz C. Vegan Diet and the Gut Microbiota Composition in Healthy Adults. Nutrients. 2021 Jul 13;13(7):2402. doi: 10.3390/nu13072402. PMID: 34371912; PMCID: PMC8308632.

9. Jang LG, Choi G, Kim SW, Kim BY, Lee S, Park H. The combination of sport and sport-specific diet is associated with characteristics of gut microbiota: an observational study. J Int Soc Sports Nutr. 2019 May 3;16(1):21. doi: 10.1186/s12970-019-0290-y. PMID: 31053143; PMCID: PMC6500072.

10. Chen Y, Yang K, Xu M, Zhang Y, Weng X, Luo J, Li Y, Mao YH. Dietary Patterns, Gut Microbiota and Sports Performance in Athletes: A Narrative Review. Nutrients. 2024 May 26;16(11):1634. doi: 10.3390/nu16111634. PMID: 38892567; PMCID: PMC11175060.

11. Allen JM, Mailing LJ, Niemiro GM, Moore R, Cook MD, White BA, Holscher HD, Woods JA. Exercise Alters Gut Microbiota Composition and Function in Lean and Obese Humans.

Med Sci Sports Exerc. 2018 Apr;50(4):747-757. doi: 10.1249/MSS.0000000000001495. PMID: 29166320.

12. Liu Y, Wang Y, Ni Y, Cheung CKY, Lam KSL, Wang Y, Xia Z, Ye D, Guo J, Tse MA, Panagiotou G, Xu A. Gut Microbiome Fermentation Determines the Efficacy of Exercise for Diabetes Prevention. Cell Metab. 2020 Jan 7;31(1):77-91.e5. doi: 10.1016/j.cmet.2019.11.001. Epub 2019 Nov 27. PMID: 31786155.

13. Porepp ODSC, Xavier MG, da Silveira LM, Lindenau I, Schellin AS, Piccoli RC, Messenburger GP, da Silva PP, Oliveira PS, Delpino FM, Pieniz S. Effect of Probiotic Supplementation on Gut Microbiota and Sport Performance in Athletes and Physically Active Individuals: A Systematic Review. J Diet Suppl. 2024;21(5):660-676. doi: 10.1080/19390211.2023.2293842. Epub 2023 Dec 26. PMID: 38148685.

14. Moreno-Pérez D, Bressa C, Bailén M, Hamed-Bousdar S, Naclerio F, Carmona M, Pérez M, González-Soltero R, Montalvo-Lominchar MG, Carabaña C, Larrosa M. Effect of a Protein Supplement on the Gut Microbiota of Endurance Athletes: A Randomized, Controlled, Double-Blind Pilot Study. Nutrients. 2018 Mar 10;10(3):337. doi: 10.3390/nu10030337. PMID: 29534465; PMCID: PMC5872755.

15. Rankin A, O’Donovan C, Madigan SM, O'Sullivan O, Cotter PD. 'Microbes in sport' -The potential role of the gut microbiota in athlete health and performance. Br J Sports Med. 2017 May;51(9):698-699. doi: 10.1136/bjsports-2016-097227. Epub 2017 Jan 25. Erratum in: Br J Sports Med. 2018 May;52(9):618. doi: 10.1136/bjsports-2016-097227corr1.. O'Donavon C [corrected to O’Donovan C]. PMID: 28432108.

16. Couvert A, Goumy L, Maillard F, Esbrat A, Lanchais K, Saugrain C, Verdier C, Doré E, Chevarin C, Adjtoutah D, Morel C, Pereira B, Martin V, Lancha AH Jr, Barnich N, Chassaing B, Rance M, Boisseau N. Effects of a Cycling versus Running HIIT Program on Fat Mass Loss and Gut Microbiota Composition in Men with Overweight/Obesity. Med Sci Sports Exerc. 2024 May 1;56(5):839-850. doi: 10.1249/MSS.0000000000003376. Epub 2024 Jan 18. PMID: 38233990.

17. Pane M, Amoruso A, Deidda F, Graziano T, Allesina S, Mogna L. Gut Microbiota, Probiotics, and Sport: From Clinical Evidence to Agonistic Performance. J Clin Gastroenterol. 2018 Nov/Dec;52 Suppl 1, Proceedings from the 9th Probiotics, Prebiotics and New Foods, Nutraceuticals and Botanicals for Nutrition & Human and Microbiota Health Meeting, held in Rome, Italy from September 10 to 12, 2017:S46-S49. doi: 10.1097/MCG.0000000000001058. PMID: 29782463.

18. Mancin L, Wu GD, Paoli A. Gut microbiota-bile acid-skeletal muscle axis. Trends Microbiol. 2023 Mar;31(3):254-269. doi: 10.1016/j.tim.2022.10.003. Epub 2022 Oct 29. Erratum in: Trends Microbiol. 2023 Mar;31(3):322. doi: 10.1016/j.tim.2023.01.003. PMID: 36319506.

19. Mańkowska K, Marchelek-Myśliwiec M, Kochan P, Kosik-Bogacka D, Konopka T, Grygorcewicz B, Roszkowska P, Cecerska-Heryć E, Siennicka A, Konopka J, Dołęgowska B. Microbiota in sports. Arch Microbiol. 2022 Jul 14;204(8):485. doi: 10.1007/s00203-022-03111-5. PMID: 35834007; PMCID: PMC9283338.

20. Donati Zeppa S, Gervasi M, Bartolacci A, Ferrini F, Patti A, Sestili P, Stocchi V, Agostini D. Targeting the Gut Microbiota for Prevention and Management of Type 2 Diabetes. Nutrients. 2024 Nov 19;16(22):3951. doi: 10.3390/nu16223951. PMID: 39599740; PMCID: PMC11597803.

21. Pérez-Castillo ÍM, Sabag-Daigle A, López-Chicharro J, Mihic N, Rueda R, Bouzamondo H. The athlete gut microbiota: state of the art and practical guidance. Benef Microbes. 2024 Apr 26;15(2):97-126. doi: 10.1163/18762891-bja00007. PMID: 38659188.

22. Liu Y, Hu Y, Ma B, Wang Z, Wei B. Gut Microbiota and Exercise: Probiotics to Modify the Composition and Roles of the Gut Microbiota in the Context of 3P Medicine. Microb Ecol. 2025 May 3;88(1):38. doi: 10.1007/s00248-025-02529-w. PMID: 40319213; PMCID: PMC12049406.

23. Jarrett H, Medlin S, Morehen JC. The Role of the Gut Microbiome and Probiotics in Sports Performance: A Narrative Review Update. Nutrients. 2025 Feb 14;17(4):690. doi: 10.3390/nu17040690. PMID: 40005018; PMCID: PMC11858190.

24. Bongiovanni T, Santiago M, Zielinska K, Scheiman J, Barsa C, Jäger R, Pinto D, Rinaldi F, Giuliani G, Senatore T, Kostic AD. A Lactobacillus consortium provides insights into the sleep-exercise-microbiome nexus in proof of concept studies of elite athletes and in the general population. Microbiome. 2025 Jan 2;13(1):1. doi: 10.1186/s40168-024-01936-4. PMID: 39748236; PMCID: PMC11697739.

25. Zhang L, Li H, Song Z, Liu Y, Zhang X. Dietary Strategies to Improve Exercise Performance by Modulating the Gut Microbiota. Foods. 2024 May 27;13(11):1680. doi: 10.3390/foods13111680. PMID: 38890909; PMCID: PMC11171530.

26. Min L, Ablitip A, Wang R, Luciana T, Wei M, Ma X. Effects of Exercise on Gut Microbiota of Adults: A Systematic Review and Meta-Analysis. Nutrients. 2024 Apr 5;16(7):1070. doi: 10.3390/nu16071070. PMID: 38613103; PMCID: PMC11013040.

27. Nolte S, Krüger K, Lenz C, Zentgraf K. Optimizing the Gut Microbiota for Individualized Performance Development in Elite Athletes. Biology (Basel). 2023 Dec 5;12(12):1491. doi: 10.3390/biology12121491. PMID: 38132317; PMCID: PMC10740793.

28. Li Y, Cheng M, Zha Y, Yang K, Tong Y, Wang S, Lu Q, Ning K. Gut microbiota and inflammation patterns for specialized athletes: a multi-cohort study across different types of sports. mSystems. 2023 Aug 31;8(4):e0025923. doi: 10.1128/msystems.00259-23. Epub 2023 Jul 27. PMID: 37498086; PMCID: PMC10470055.

29. Fontana F, Longhi G, Tarracchini C, Mancabelli L, Lugli GA, Alessandri G, Turroni F, Milani C, Ventura M. The human gut microbiome of athletes: metagenomic and metabolic insights. Microbiome. 2023 Feb 14;11(1):27. doi: 10.1186/s40168-023-01470-9. PMID: 36782241; PMCID: PMC9926762.

30. Miranda-Comas G, Petering RC, Zaman N, Chang R. Implications of the Gut Microbiome in Sports. Sports Health. 2022 Nov-Dec;14(6):894-898. doi: 10.1177/19417381211060006. Epub 2022 Jan 17. PMID: 35034531; PMCID: PMC9631033.

31. Barton W, Cronin O, Garcia-Perez I, Whiston R, Holmes E, Woods T, Molloy CB, Molloy MG, Shanahan F, Cotter PD, O'Sullivan O. The effects of sustained fitness improvement on the gut microbiome: A longitudinal, repeated measures case-study approach. Transl Sports Med. 2021 Mar;4(2):174-192. doi: 10.1002/tsm2.215. Epub 2020 Dec 13. PMID: 34355132; PMCID: PMC8317196.

32. Hughes RL, Holscher HD. Fueling Gut Microbes: A Review of the Interaction between Diet, Exercise, and the Gut Microbiota in Athletes. Adv Nutr. 2021 Dec 1;12(6):2190-2215. doi: 10.1093/advances/nmab077. PMID: 34229348; PMCID: PMC8634498.

33. Smith KA, Pugh JN, Duca FA, Close GL, Ormsbee MJ. Gastrointestinal pathophysiology during endurance exercise: endocrine, microbiome, and nutritional influences. Eur J Appl Physiol. 2021 Oct;121(10):2657-2674. doi: 10.1007/s00421-021-04737-x. Epub 2021 Jun 15. PMID: 34131799.

34. Jaago M, Timmusk US, Timmusk T, Palm K. Drastic Effects on the Microbiome of a Young Rower Engaged in High-Endurance Exercise After a Month Usage of a Dietary Fiber Supplement. Front Nutr. 2021 Apr 30;8:654008. doi: 10.3389/fnut.2021.654008. PMID: 33996876; PMCID: PMC8119783.

35. Barton W, Penney NC, Cronin O, Garcia-Perez I, Molloy MG, Holmes E, Shanahan F, Cotter PD, O'Sullivan O. The microbiome of professional athletes differs from that of more sedentary subjects in composition and particularly at the functional metabolic level. Gut. 2018 Apr;67(4):625-633. doi: 10.1136/gutjnl-2016-313627. Epub 2017 Mar 30. PMID: 28360096.

36. Jäger R, Mohr AE, Carpenter KC, Kerksick CM, Purpura M, Moussa A, Townsend JR, Lamprecht M, West NP, Black K, Gleeson M, Pyne DB, Wells SD, Arent SM, Smith-Ryan AE, Kreider RB, Campbell BI, Bannock L, Scheiman J, Wissent CJ, Pane M, Kalman DS, Pugh JN,

Ter Haar JA, Antonio J. International Society of Sports Nutrition Position Stand: Probiotics. J Int Soc Sports Nutr. 2019 Dec 21;16(1):62. doi: 10.1186/s12970-019-0329-0. PMID: 31864419; PMCID: PMC6925426.