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Probiotic modulation of the athletic gut: Implications for intestinal barrier function, immunity and exercise-related stress

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ABSTRACT

Background: Physical activity is associated with multiple systemic adaptations, some of which appear to be mediated by the gut microbiota. In athletes, especially those engaged in endurance sports, intense training may alter gut barrier function, immune responses and gastrointestinal homeostasis. In this context, probiotics have attracted growing interest as a potential nutritional strategy to support gut health and exercise adaptation.
This narrative review aims to summarize current evidence on the interactions between gut microbiota, physical activity and probiotic supplementation in athletes, with particular attention to gastrointestinal health, immune modulation, oxidative stress and exercise-related physiological responses.
Materials and methods: A narrative review of the literature published between 2005 and 2025 was conducted using major scientific databases, including PubMed, Scopus and Web of Science. The literature was selected on the basis of relevance to the topic, with emphasis on studies involving athletes, endurance exercise, gut microbiota and probiotic use.
Results: The available literature suggests that regular physical activity may influence gut microbiota composition and metabolic activity, while probiotic supplementation may help support gastrointestinal integrity, modulate immune and inflammatory responses and reduce selected exercise-related symptoms in athletes. However, findings remain heterogeneous because of differences in study design, probiotic strains, dosages, intervention duration and athlete populations.
Conclusions: Probiotic supplementation may represent a promising supportive strategy for modulating the athletic gut, particularly in relation to intestinal barrier integrity, immune regulation and exercise-associated physiological stress. Nevertheless, current evidence remains heterogeneous and further well designed studies are needed to clarify strain-specific effects and their relevance to athletic performance and recovery.

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1. Introduction

Probiotics are commonly described as live microorganisms that, when administered in adequate amounts, may confer health benefits on the host [1–4]. In biomedical and nutritional research, probiotic-related interventions have been investigated in relation to host microbe interactions, immune regulation, metabolic homeostasis and mucosal health [5,6,7,8,9,10]. Probiotic supplementation may influence gut microbiota (GM) composition by promoting microbial balance, supporting the growth of beneficial microorganisms and helping restore gut homeostasis under physiologically stressful conditions [11–16]. Probiotic supplementation may contribute to host health through several mechanisms. These mechanisms include the production of bioactive antimicrobial compounds, inhibition of pathogen adhesion to the intestinal mucosa, reinforcement of intestinal barrier function and modulation of the immune responses.

Probiotic products may contain a single strain or a combination of different microorganisms, most commonly lactic acid bacteria, Bifidobacterium species and, in some cases, *Saccharomyces boulardii* [17–20]. They are available in different formulations, including capsules, tablets, powders and fermented foods, such as yogurt and sour milk. Their effectiveness depends on strain specificity, dose, formulation, survival during gastrointestinal transit and interaction with the host intestinal environment [21–26]. Although no universally accepted minimum effective dose has been established for all probiotic products, doses used in clinical and nutritional studies are generally expressed in colony forming units (CFU) and vary according to strains, formulation and intended use [27–32]. These aspects are particularly relevant in athletes, in whom training load, competition schedules, dietary manipulation, travel, psychological stress and gastrointestinal symptoms may influence gut microbial balance and intestinal barrier function. Intense and prolonged exercise may increase gut permeability, alter immune responses and contribute to gastrointestinal discomfort, thereby supporting interest in probiotic supplementation as a potential strategy to preserve gut homeostasis during periods of high physiological stress [33–40]. In this context, the aim of the present narrative review is to discuss the physiological, immunological and gastrointestinal interactions among gut microbiota, probiotic supplementation and physical activity, with particular attention to athletes and endurance exercise [41–45].

2. Materials and Methods

This narrative review was guided by the following question: “Which probiotic strains have been associated with potential benefits in gastrointestinal integrity, immune modulation, oxidative stress and exercise-related outcomes in athletes, particularly in endurance disciplines?”

Rather than testing a prespecified hypothesis in a systematic-review framework, we used this question to organize the literature around clinically relevant domains, including intestinal barrier function, short-chain fatty acid (SCFA) production, immune responses and oxidative stress in athletes exposed to intense physical training.

To address this topic, we synthesized clinical and experimental studies published between 2005 and 2025, with particular attention to strain-specific outcomes, study design and the physiological mechanisms proposed in the literature. Seminal articles published before 2005 were also considered when necessary to support definitions, historical background or established physiological concepts.

This work is not a systematic review or meta-analysis and was not intended to provide an exhaustive quantitative assessment of the evidence. Instead, it offers an interpretive narrative synthesis aimed at integrating current knowledge on probiotic supplementation, gut microbiota composition and their potential implications for athletic health and performance.

Articles were identified through searches of major scientific databases (PubMed, Scopus and Web of Science) using combinations of the following terms: “probiotics”, “gut microbiota”, “athletes”, “endurance sports”, “exercise”, “physical performance”, “gut-brain axis”, “gut-lung axis”, “gut-heart axis” and “metabolic endotoxemia”. Boolean operators (AND/OR) were used to refine the search results.

Eligibility criteria included peer-reviewed articles published in English between January 2005 and May 2025, studies involving adult human participants, original research articles and studies examining the effects of probiotics or gut microbiota on athlete health or performance. Original human studies were prioritized for the synthesis of athlete-related outcomes. Review articles, systematic reviews, and position statements were considered only when useful for background information, definitions or contextual interpretation.

Although no formal systematic review protocol (e.g., PRISMA) was applied, the selection process followed a rigorous thematic and methodological approach to ensure relevance and consistency with the aims of the review. The final selection of studies was based on thematic relevance, methodological quality, population characteristics and direct applicability to athlete health, gastrointestinal function, immune modulation, oxidative stress or exercise-related outcomes.

3. Discussion

3.1. The human gut microbiota

The human gut microbiota (GM) refers to the community of microorganisms—primarily bacteria, but also viruses, protozoa, fungi and archaea—that inhabit the gastrointestinal tract. The term “gut microbiome” is often used to indicate the collective genomes of these microorganisms. In humans, the GM can be considered a highly complex ecosystem that contributes to several functions essential to host physiology [46–49]. It plays an important role in metabolism, immune regulation, maintenance of the intestinal barrier and systemic inflammatory balance. Among the mechanisms involved in host–microbe communication is the interaction with toll-like receptors (TLRs), which detect microbial components and activate downstream immune pathways [50–54]. In particular, TLR4 recognizes lipopolysaccharide, whereas TLR2 is mainly involved in the recognition of peptidoglycan and related cell-wall components; activation of these receptors promotes cytokine production and contributes to host defense. At the same time, dysregulated activation of inflammatory pathways may be associated with chronic inflammatory conditions [55–57]. The GM is shaped by several host- and environment-related factors, including diet, antibiotic exposure, infections, age and lifestyle. In adulthood, the gut microbial ecosystem is relatively stable but remains responsive to external stimuli such as dietary patterns and physical activity. Therefore, in athletes the GM should be considered a dynamic interface between diet, training load, intestinal barrier integrity, immune regulation and systemic metabolic adaptation [58–67].

3.2. Physical activity, the gut-brain axis and the gut-muscle axis

Physical activity is a well-established strategy for the prevention and management of chronic disease. Emerging evidence suggests that some of these benefits are mediated, at least in part, by changes in the gut microbiome. Exercise improves several metabolic and inflammatory parameters and promotes adaptive changes in human physiology; however, the biomarkers and molecular mediators underlying these pleiotropic effects remain only partially understood [68–70]. Recent studies suggest a dynamic relationship between the GM and the level of physical activity, including in high-performance athletes. Early investigations reported notable differences in the composition of the GM between competitive athletes and inactive individuals [71,72]. Conversely, prolonged physical stress may transiently increase intestinal permeability and favor inflammatory responses. Several studies therefore support the existence of a bidirectional interaction between the gut and the musculoskeletal system, the so-called gut–muscle axis, which intersects with the gut–brain axis (Fig. 1) [73–75].

Myokines released during exercise, such as IL-6, may stimulate glucagon-like peptide 1 (GLP-1) secretion, further linking muscle activity to gut microbiota modulation. Additional support for the existence of a gut–muscle axis comes from the production of SCFAs by the GM. These metabolites can serve as energy substrates for muscle mitochondria and may contribute to the regulation of glucose metabolism [76–79]. A common finding in both animal and human studies is that exercise can increase species richness (alpha diversity). Physical activity has also been associated with a higher abundance of butyrate-producing bacteria, which is relevant because butyrate contributes to intestinal barrier integrity and may help limit the translocation of toxic compounds and microorganisms from the gut lumen. Overall, experimental animal models have helped clarify the physiological and biochemical effects of exercise on the GM, whereas cross-sectional and longitudinal studies in humans have attempted to describe how physical activity influences adult gut microbiota composition [80–82].

Several human studies support these observations. For example, professional rugby players have been shown to display greater GM diversity than control groups with different body mass index (BMI) values, together with differences in dietary habits (especially protein intake) and a more favorable metabolic and inflammatory profile. In premenopausal women, exercise did not always induce major changes in overall microbial diversity, but sedentary behavior and longer uninterrupted sitting time were inversely associated with microbial richness, whereas sustained physical activity was associated with increased abundance of health-promoting bacteria such as Bifidobacterium spp., *Roseburia hominis*, *Akkermansia muciniphila*, and *Faecalibacterium prausnitzii* [83–86]. A case report involving four healthy, well-trained male athletes who completed a 33-day, 5000 km transatlantic rowing race also showed an increase in GM diversity during the event. Reported compositional changes included higher abundance of butyrate-producing species, such as *R. hominis* and members of the genus Subdoligranulum, as well as taxa associated with better metabolic health, including *Dorea longicatena*. Functional analyses suggested increased potential for amino acid and fatty acid biosynthesis. Some of these adaptations persisted at the 3-month follow-up, although post-race trajectories differed among athletes and appeared to be influenced by factors such as antibiotic use and dietary changes related to frozen or dried foods consumed during the race [87–92].

SCFAs represent a major class of bacterial metabolites and play a critical role in host metabolism and immunity through local and systemic actions on multiple targets. In marathon runners, an increased abundance of Veillonella has been associated with enhanced SCFA production via lactate metabolism, further supporting the concept that exercise and the GM interact in ways that may influence performance and recovery [93–95].

3.3. Mechanisms of action of probiotics

Although the exact mechanisms of action of probiotics have not been fully elucidated, several complementary pathways have been proposed (Fig. 2). As noted above, the most widely used probiotics are lactic acid-producing microorganisms, especially members of the Lactobacillaceae family and Bifidobacterium species [96–98]. The lactic, propionic and acetic acids produced by these microorganisms can lower luminal pH and may help suppress the growth of pathogenic bacteria, thereby contributing to restoration of GM balance. Another proposed mechanism is the production of bioactive compounds—such as hydrogen peroxide, bacteriocins, biosurfactants and other organic acids—with direct or indirect antimicrobial effects [99–102].

For example, Lacticaseibacillus rhamnosus GG has been reported to produce low-molecular-weight compounds capable of inhibiting the growth of a wide range of Gram-positive and Gram-negative bacteria. *Saccharomyces boulardii*, a non-pathogenic yeast, has also been widely studied, particularly in the management of Clostridioides difficile infection, where it may exert protective effects through the production of a protease able to reduce the activity of toxins A and B [103–108].

Probiotics may also reduce colonization of the gastrointestinal and urinary epithelium by pathogenic microorganisms by competing for adhesion sites and limiting pathogen attachment to mucosal surfaces. Members of the Lactobacillaceae family, for instance, have been shown to inhibit adhesion of *Escherichia coli*, *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* to uroepithelial cells and to intestinal epithelial cells, while also promoting the formation of protective glycoprotein-rich barriers [109–111]. At the same time, several probiotic strains may strengthen the intestinal epithelial barrier by stabilizing tight junctions

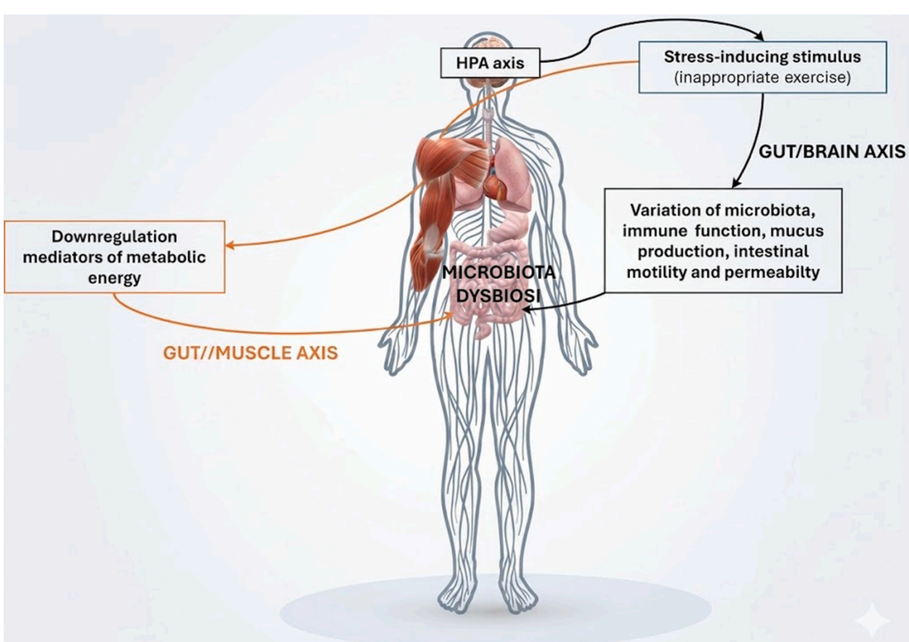

Fig. 1. Interconnections between the gut-brain and gut-muscle axes (created by the authors).

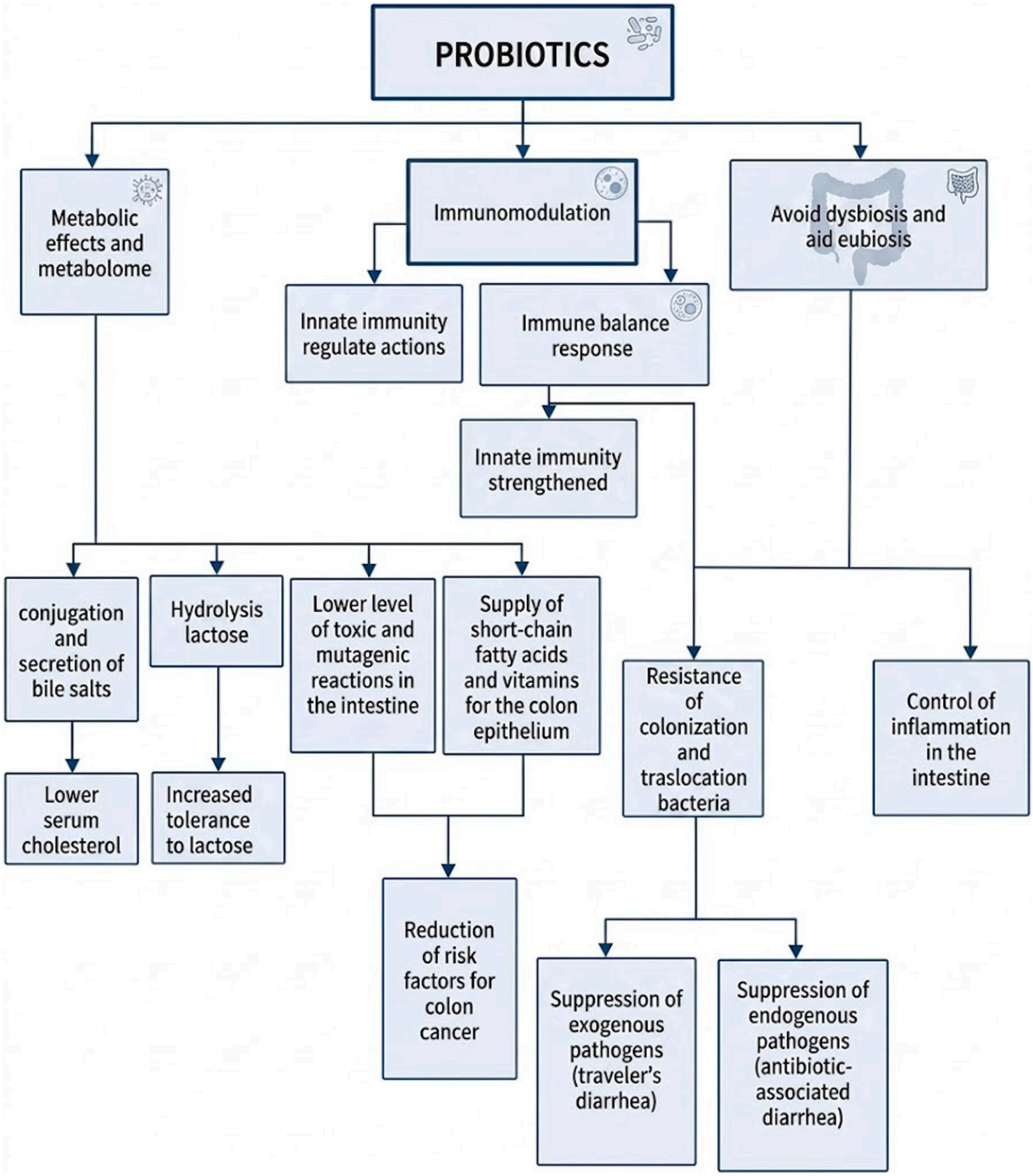

Fig. 2. Main mechanisms of action of probiotic supplementation.

Table 1
Clinical conditions associated with beneficial effects of probiotic supplementation.

The beneficial effects of probiotic strains					
Acute diarrheal syndromes	**Irritable bowel syndrome**	**Inflammatory bowel disease**	**Antibiotic-associated diarrhea and *C. difficile* infections**	**Allergic conditions**	**Urogenital tract infections**
Lactobacillus rhamnosus GG and *Limoselactobacillus reuteri* are mainly used.	*Lactobacillaceae* phyla and *Bifidobacteria* spp. are mainly used to treat but with results that have not yet been confirmed.	Probiotics seem to have the potential to improve these imbalances, constituting an alternative option, compared to antibiotics, for the prevention and treatment of these diseases.	*Lactobacillaceae* phyla and *Saccharomyces boulardii* are mainly used.	There are studies that have shown the beneficial effects of *Lactobacillus rhamnosus* GG in the treatment of atopic dermatitis in young children, with a reduction in symptoms of up to 50%.	*Lactobacillaceae* phyla specially *Lactobacillus crispatus* and *Lactobacillus iners*, are the predominant microorganisms found in the vagina of healthy premenopausal women.

and reducing intestinal permeability. Immunomodulation represents another major mechanism. Experimental studies suggest that selected probiotic strains can enhance innate immune responses, modulate cytokine production and support mucosal immunity. In children with acute rotavirus gastroenteritis, administration of *L. rhamnosus* GG has been associated with increased production of IgA, IgG and IgM, with a corresponding reduction in symptom duration [112–115]. In light of these mechanisms, probiotic supplementation has been associated with a range of beneficial effects in humans. Although Table 1 summarizes broader clinical contexts in which probiotics have been investigated, the relevance of these mechanisms for athletes mainly concerns intestinal barrier integrity, mucosal immunity, inflammatory regulation, oxidative stress and exercise-related gastrointestinal symptoms [116–119].

Beyond their general roles in maintaining gut barrier integrity and modulating immunity, probiotics may influence several molecular pathways that are relevant to athletic performance. Experimental and clinical data suggest that:

- SCFAs generated by gut microbes and potentially supported indirectly by probiotic supplementation can act on G-protein-coupled receptors such as GPR41 and GPR43, thereby influencing energy metabolism, mitochondrial biogenesis, and insulin sensitivity in skeletal muscle [120–123].
- Lactiplantibacillus plantarum PS128 may modulate dopaminergic signaling through altered tyrosine metabolism and changes in oxidative stress markers, potentially contributing to better neuromuscular coordination and fatigue resistance in athletes [124–129].
- *Bifidobacterium longum* has been reported to attenuate Lipopolysaccharide (LPS)-induced systemic inflammation through modulation of the TLR4/NF-κB (Nuclear factor kappa-light-chain-enhancer of activated B cells) pathway, which may help counter exercise-induced immune disturbances [130–134].
- In experimental settings, Lacticaseibacillus rhamnosus GG has been associated with increased expression of tight-junction-related proteins, including claudins, occludin and ZO-1 (Zonula Occludens-1), suggesting a potential role in supporting intestinal barrier function [135].

Taken together, these mechanisms suggest that different probiotic strains may target distinct physiological domains, including immune function, neuromuscular performance, metabolic efficiency and intestinal barrier integrity (Table 2) [136–139].

3.4. Athletes and probiotic supplementation

The benefits of regular physical exercise are well established across age groups and in both sexes, whether activity is performed at an amateur, semi-professional, or professional level. Athletes are frequently exposed to high training loads that may influence gastrointestinal function, immune balance, oxidative stress and recovery (Fig. 3) [140–144].

Table 2
Mechanistic links between probiotics and exercise-related outcomes.

Strain	Mechanism	Pathway /Molecule	Athletic Effect
L. plantarum PS128	Modulation of neurotransmitters	↑ Tyrosine, dopamine	Reduced anxiety, better focus
L. rhamnosus GG	Reinforcement of gut barrier	↑ Claudin, Occludin, ZO-1	↓ GI symptoms under stress
B. longum	Suppression of systemic inflammation	↓ LPS, TLR4/ NF-κB	Better immune resilience
F. prausnitzii, Roseburia spp.	Production of SCFAs	GPR41/GPR43 activation, ↑ butyrate	Improved energy metabolism, ↓ fatigue
L. casei Shirota	Immunostimulation, anti-inflammatory cytokine modulation	↑ IgA, ↓ TNF-α, ↑ IL-10	Fewer respiratory infections

Despite the recognized health benefits of physical activity, athletes, particularly at the professional level, may face challenges such as overuse injuries, stress fractures, gastrointestinal complaints, psychological distress, and, in some cases, disordered eating patterns. These conditions may affect both physical performance and mental health, thereby supporting interest in adjunctive interventions (Fig. 4). Despite the growing interest in probiotic supplementation in athletes, the current literature provides limited and sometimes conflicting evidence on sex-specific responses [145–148]. Several randomized controlled trials enrolled both male and female participants, yet outcomes were often not stratified by sex or appeared to differ between sexes. Female athletes have occasionally shown less consistent responses in terms of immune modulation, gastrointestinal symptoms, or microbiota changes after probiotic supplementation. These differences may reflect hormonal fluctuations, baseline differences in microbiota composition or variability in systemic inflammatory status. In addition, conditions such as the Female Athlete Triad and relative energy deficiency in sport (RED-S) may influence probiotic efficacy and gut microbiota balance. While the Female Athlete Triad is specific to female athletes, RED-S can affect both male and female athletes and should therefore be considered in sex-specific analyses [149–152]. Future studies should therefore include sex specific analyses or be specifically designed to investigate differential physiological and microbial responses in both male and female athletes.

Within this framework, scientific interest in probiotics has grown because they may help modulate key components of the athletic gut, including microbial composition, epithelial barrier integrity, mucosal immune responses, and selected exercise-related symptoms [153–157]. Probiotics, frequently based on lactic acid bacteria, are thought to modulate gut microbiota and strengthen mucosal immune defenses in the gastrointestinal and respiratory tracts. This topic is particularly relevant in athletes because intense exercise may compromise mucosal integrity and contribute to symptoms such as nausea, abdominal pain, and diarrhea [158]. Nutritional strategies that help preserve barrier function are therefore increasingly being explored as supportive tools for reducing exercise-related gastrointestinal and respiratory symptoms and for promoting systemic resilience [159–161].

Additional evidence comes from studies of other strains and multi-strain formulations. In a double-blind randomized trial, Lactiplantibacillus plantarum PS128 administered for 4 weeks to elite triathletes was associated with favorable changes in oxidative, inflammatory and metabolic pathways, suggesting a possible role in maintaining performance during heavy training loads. By contrast, Ligilactobacillus salivarius did not show significant effects on respiratory infections, immune cell counts, salivary IgA, or lysozyme levels in endurance athletes, indicating that benefits are likely to be strain specific. A combination of Lacticaseibacillus rhamnosus and *L. paracasei* administered for 4 weeks has been associated with improved antioxidant status and better perceived intestinal well-being in young athletes, supporting a potential role in counteracting exercise-induced oxidative stress [162,163].

Multi-strain supplementation has also produced promising results. In one trial, high-level athletes undergoing intense winter training received a daily probiotic mixture containing *Bifidobacterium bifidum* W23, B. lactis W51, *Enterococcus faecium* W54, *Lactobacillus acidophilus* W22, Levilactobacillus brevis W63 and *Lactococcus lactis* W58 (1 × 10^10 CFU/day) for 12 weeks. Compared with placebo, probiotic supplementation was associated with more stable tryptophan concentrations after intense exercise and a lower number of athletes experiencing one or more upper respiratory tract infections, although no significant improvement in performance was detected. In another randomized double-blind trial involving 23 young male endurance athletes, the same multi-strain preparation administered for 14 weeks significantly reduced fecal zonulin concentrations, suggesting improved intestinal barrier integrity; reductions in TNF-α and protein carbonyls were observed but did not reach statistical significance [164–167].

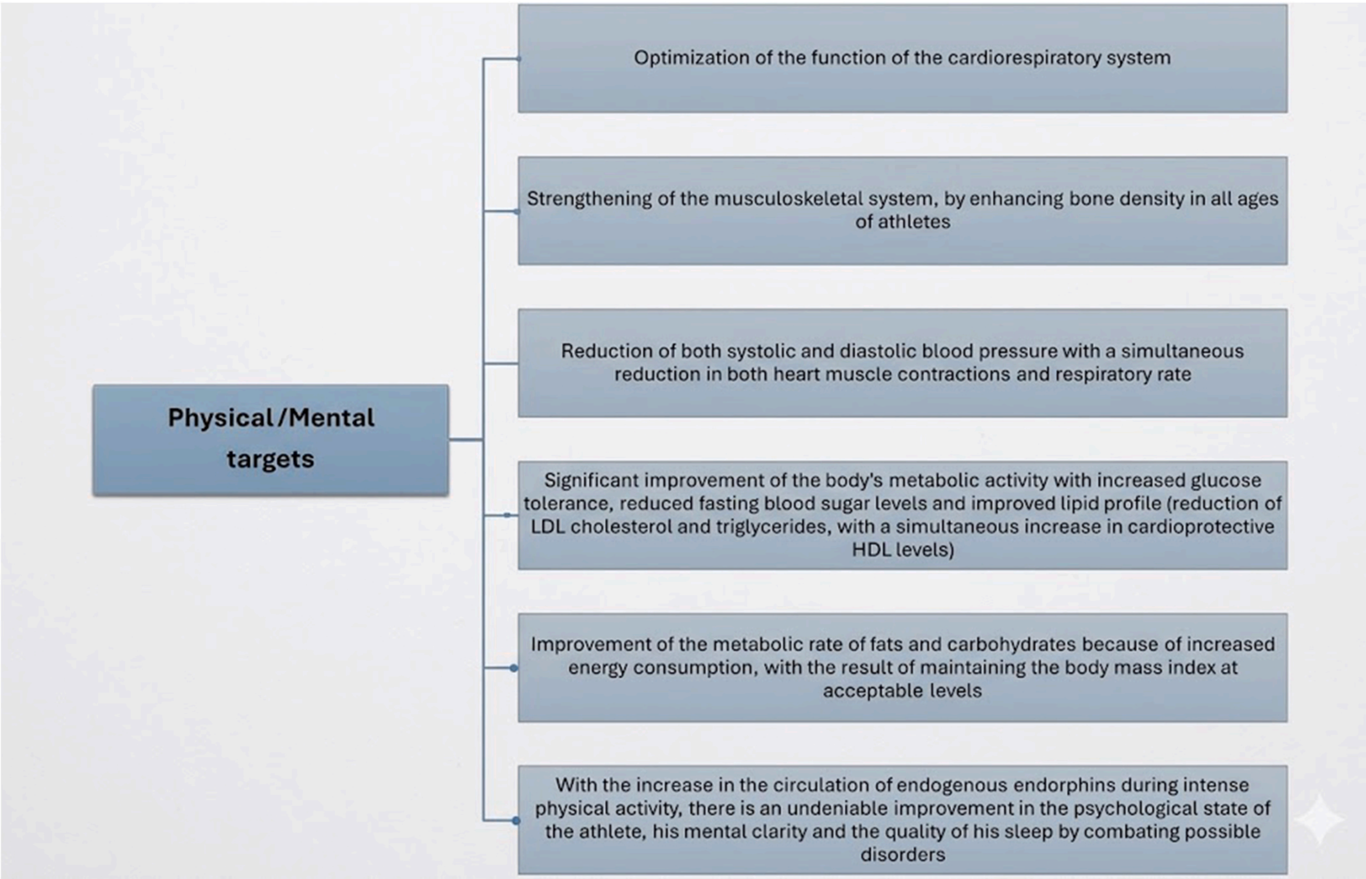

Fig. 3. Main physical and mental health benefits of regular physical activity in athletes.

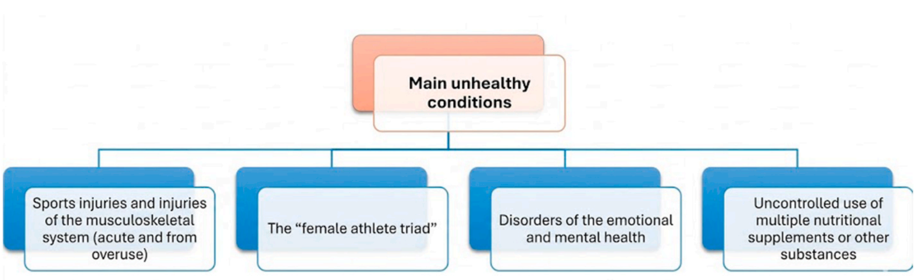

Fig. 4. *Ma*in health risks associated with intense or unbalanced athletic practice.

Beyond supplementation trials, observational and experimental evidence also supports a link between exercise, microbial metabolites and performance. For example, after the Boston Marathon, professional athletes showed an increased abundance of Veillonella spp., bacteria able to metabolize lactate. In experimental models, administration of *Veillonella atypica* was associated with lower inflammatory cytokine levels after exercise and improved endurance performance [168]. Overall, the available literature suggests that probiotic supplementation may support intestinal barrier function, immune balance and oxidative status in endurance athletes, but larger and better-controlled studies are still needed to confirm these findings and define their practical relevance (Table 3).

To improve the translational value of this review, Table 4 provides a concise summary of practical considerations derived from the available

Table 3
Probiotic strains studied in relation to gastrointestinal, immune, oxidative and performance related outcomes in athletes.

Probiotic Strain	Effect	Study Outcome	Study Design	Conclusion	Reference
Limosilactobacillus fermentum	Gastrointestinal health, reduced symptoms	Decreased gastrointestinal distress and improved respiratory symptoms in endurance athletes	Randomized, double-blind, placebo-controlled clinical trial	Beneficial for gastrointestinal and respiratory health	Cox et al., 2010
Lacticaseibacillus rhamnosus and Lacticaseibacillus paracasei subsp. paracasei	Reduction of oxidative stress, improved intestinal health	Increased antioxidant levels and improved intestinal barrier function in trained men	Randomized controlled trial	Positive effects on oxidative stress and gut health	Lamprecht et al., 2012

Table 4
Evidence informed practical considerations for probiotic supplementation in athletes.

Goal	Recommended Strain(s)	Duration	Notes
Reduce GI symptoms	*L. fermentum*, *L. plantarum*, Multi-strain	4–12 weeks	Especially relevant to endurance athletes; may reduce training related GI distress
Support immune system	*L. casei Shirota*, *Bifidobacterium bifidum*	≥4 weeks	May reduce URTI incidence and support selected mucosal immune markers
Improve oxidative stress	*L. rhamnosus*+*L. paracasei*	≥4 weeks	May improve selected oxidative stress or antioxidant markers
Enhance gut barrier integrity	Multi-strain (e.g., *L. acidophilus*, *B. lactis*)	≥8 weeks	May support intestinal barrier integrity, including reductions in zonulin in selected studies
Support general gut health	*L. rhamnosus*, *L. paracasei*	≥4 weeks	Potential support for microbiota composition and overall gut health

literature [169–171].

3.5. Limitations and future directions

Many of the included studies were limited by small sample sizes and by substantial heterogeneity in probiotic strains, doses, intervention durations, outcome measures and athlete populations, thereby reducing comparability and statistical power. In addition, potentially important confounders (including diet, antibiotic exposure, training intensity and baseline microbiota composition) were often insufficiently controlled [172–174]. Because this work was designed as a narrative review, no formal risk of bias assessment or quantitative evidence grading was performed. Future research should adopt more standardized protocols, include larger randomized controlled trials and better account for life-style related variables in order to clarify the effects of probiotics in athletes. Well conducted meta-analyses may also help define strain specific outcomes [175–177].

4. Conclusions

Current evidence suggests that probiotic supplementation is generally well tolerated in athletes and may provide selected benefits, particularly in relation to gastrointestinal health, immune function and exercise-associated physiological stress. These findings support the concept of the athletic gut as a potential target for nutritional strategies aimed at maintaining gastrointestinal resilience during periods of high training load.

The observed effects appear to be strain-specific and are likely influenced by dose, duration of supplementation, sport discipline and the athlete's baseline condition. Among the most promising approaches are *L. rhamnosus*, *L. paracasei* and selected multi-strain combinations, which have shown potential for reducing respiratory and gastrointestinal symptoms and for supporting gut barrier function.

However, the exact mechanisms remain only partially understood and outcomes vary considerably across studies. Future research should focus on larger, sport-specific clinical trials in order to establish more robust evidence and support the development of evidence-based and context specific recommendations.

Informed consent statement

Not applicable.

Author contributions

Conceptualization, I.A.C., G.M. and A.D.I.; methodology, A.S., S.S. and A.M.I.; software, G.M., G.D. and M.S.; validation, F.C. and C.C.; formal analysis A.P., F.I. and G.D.; resources, I.A.C., A.S. and S.S.; data curation A.S., A.M.I. and M.S.; writing—original draft preparation, I.A. C., G.M., A.D.I., A.S., F.C. and C.C.; writing—review and editing, F.I., S. S., A.P., A.M.I., M.S. and G.D.; visualization A.D.I.; supervision, F.I.; project administration, A.S. All authors have read and agreed to the published version of the manuscript.

Institutional review board statement

Not applicable.

Data availability statement

No new datasets were generated or analyzed during the present narrative review. All data discussed are available in the cited published literature.

Abbreviation	Definition
BMI	Body Mass Index
CFU	Colony-Forming Units
GLP-1	Glucagon-Like Peptide 1
GM	Gut Microbiota
Ig	Immunoglobulins
LPS	Lipopolysaccharide
NF-κB	Nuclear factor kappa-light-chain-enhancer of activated B cells
RED-S	Relative Energy Deficiency in Sport
SCFAs	Short-Chain Fatty Acids
TLRs	Toll-Like Receptors
URTI	Upper Respiratory Tract Infection
ZO-1	Zonula Occludens-1

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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