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REVIEW ARTICLE

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Prebiotics in sport and exercise: current evidence, practical applications, and methodological considerations

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ABSTRACT

Background: Prebiotics are selectively utilized by the host microbiota and can confer health and/or performance benefits, in part through increasing the abundance of beneficial gut microorganisms and their metabolites. While several studies have shown promising initial findings, high-quality scientific evidence examining the effects of prebiotics on athlete performance, health and wellbeing remains limited.

Methods: This narrative review summarizes the current available evidence on prebiotic intake in athletic populations, including effects on gastrointestinal structure and function, immune responses, recovery, sleep, wellness, mood and exercise performance. In areas where there is limited evidence in athletic cohorts, but a physiological rationale for a benefit, findings from sedentary and/or clinical populations are evaluated, and the potential relevance of these findings to athletes are discussed. Finally, considerations for practitioners around the use of prebiotics with athletes are provided, and recommendations for designing future prebiotic-based research are explored.

Results: Despite the limited existing literature around prebiotic use in athletes, there are several studies that indicate their potential to improve gut barrier integrity and reduce the incidence/severity of gastrointestinal symptoms. Data also indicates that prebiotics can increase salivary Immunoglobulin A secretion rate and reduce the duration and/or severity of upper respiratory symptoms in trained individuals. Other areas with emerging evidence that warrant further investigation in athletic populations include prebiotics' ability to support exercise adaptation and recovery, promote sleep improvements and enhance mood and cognitive function. The interpretation of current studies is limited by the lack of gut microbiome and metabolome measures and the absence of robust performance measures following a period of prebiotic supplementation. Well-controlled, adequately powered studies incorporating these outcomes are needed to determine the contexts in which prebiotic intake can meaningfully improve health and performance metrics, and to elucidate the underlying physiological mechanisms of any beneficial effects.

Conclusion: Prebiotic intake represents a promising intervention to attenuate exercise-induced disturbances to the intestinal epithelium, reduce exercise-associated gastrointestinal symptoms, and lower the duration/severity of upper respiratory symptoms in athletes. Future studies should prioritize high-quality performance assessments, alongside comprehensive microbiome and metabolome profiling, to elucidate mechanistic effects. Areas with limited current evidence such as recovery, sleep, mood, cognitive function, bone health and nutrient absorption in athlete cohorts should also be further explored.

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1. Introduction

1.1 The unique demands of the elite athletic performance and the athlete microbiome

Elite athletes are exposed to unique physiological and psychological challenges, with high training loads, demanding competition schedules, limited recovery windows, and frequent international travel. These collective stressors can compromise immunity, elevating the risk of acute upper respiratory symptoms (URS)

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and gastrointestinal symptoms (GIS) [1–6]. Intense training periods can reduce salivary Immunoglobulin A (sIgA) secretion [7] and alter type 1T lymphocyte distribution [8], resulting in the "J-shaped" relationship between exercise dose and URS susceptibility [9]. Acute vigorous exercise also increases intestinal permeability [10], with proposed mechanisms including splanchnic hypoperfusion and hyperthermia [11]. Reduced gut barrier integrity results in microbial translocation, which can trigger immune system activation and inflammatory cytokine release [5], emphasizing the bidirectional relationship between gut barrier disturbances and immune/inflammatory responses. Given the role that the gut environment plays in regulating both gastrointestinal (GI) integrity and immune function, dietary biotic interventions, such as prebiotics, may be beneficial to athletes.

The gut microbiome refers to the collective genomes of gut-residing microorganisms [12], and its composition can be influenced by many factors, including age [13], hereditary factors [14], smoking [15], psychological stress [16], diet [17], and exercise [18]. Gut microbial diversity can be characterized, indicating the variety and distribution of microorganisms within the gut ecosystem. A measure that is commonly used to quantify differences in microbiome composition is alpha diversity, which reflects within-sample species richness and evenness [19]. Higher levels of physical activity in athletic populations are associated with greater gut microbial diversity and an increased abundance of beneficial taxa [20–22], whereas sedentary behavior demonstrates the opposite pattern [23].

Acute high-intensity exercise can induce rapid, beneficial shifts in the gut microbiome, increasing the abundance of health-promoting taxa [24]. Consequently, athletes may exhibit differences in day-to-day variability in both composition and function of the gut microbiome compared with sedentary individuals. Throughout an athletic career, sustained training exposure, combined with higher energy and macronutrient intake are likely to influence the composition and function of the gut microbiome. These combined influences are associated with greater microbial diversity in elite athletes compared with age-, sex-, and size-matched non-athletic controls [25,26]. In addition, sport-specific dietary practices appear to shape microbial profiles. For example, endurance athletes consuming high-carbohydrate diets often present *Prevotella*-dominant bacterial profiles, whereas higher protein and animal fat intakes, more common in strength-based disciplines, are linked to *Bacteroides* dominance [27].

The physiological and training demands of each sport may also influence gut microbiome composition and function, independent from diet. Athletes from "high dynamic" sports show the most pronounced compositional differences, whereas sports with both high dynamic and static demands demonstrate the greatest differences in functional potential [28]. These distinctions also extended to metabolomic profiles [28]. Cardiorespiratory fitness [29], training volume [30], performance standards [30] and BMI [25] can also influence taxonomic richness, highlighting how the physical demands and body size/composition requirements of a sport may influence the gut microbiome. Evidence suggests that gut microbial diversity also differs between sexes [31–33] and such differences appear to extend to athletes [34], although conflicting data does exist [35]. Collectively, evidence suggests that athletic training is associated with increased microbial diversity and abundance of beneficial taxa, with outcomes modulated by training, sporting demands, diet and lifestyle factors (Figure 1). The unique gut microbiome composition of athletes may influence the selective fermentation of prebiotics by gut microbes and therefore could potentially impact their effectiveness.

Despite the beneficial effects associated with high physical activity levels, other factors associated with elite athlete's lifestyles may result in unfavorable changes to the gut microbiome. Reductions in alpha diversity have been noted following international travel to competitions [36], and after periods of high training load [37]. Athletes often have disrupted sleep due to late fixtures and travel-related circadian disruptions [38]. This disrupted sleep may induce changes in the gut microbiome [39], while changes in gut microbial composition may, in turn, impact sleep quality [40], suggesting a bidirectional relationship. Interventions to mitigate these negative impacts on the microbiome are therefore warranted.

1.2 Defining a prebiotic

Prebiotics, the focus of this review, present a potential intervention to increase gut microbial diversity, increase the abundance of favorable microbes and promote beneficial metabolomic changes. The term prebiotic was first coined by Glenn Gibson and Marcel Roberfroid in 1995 [41] and the exact definition has been refined multiple times since [41]. The current definition by The International Scientific Association for

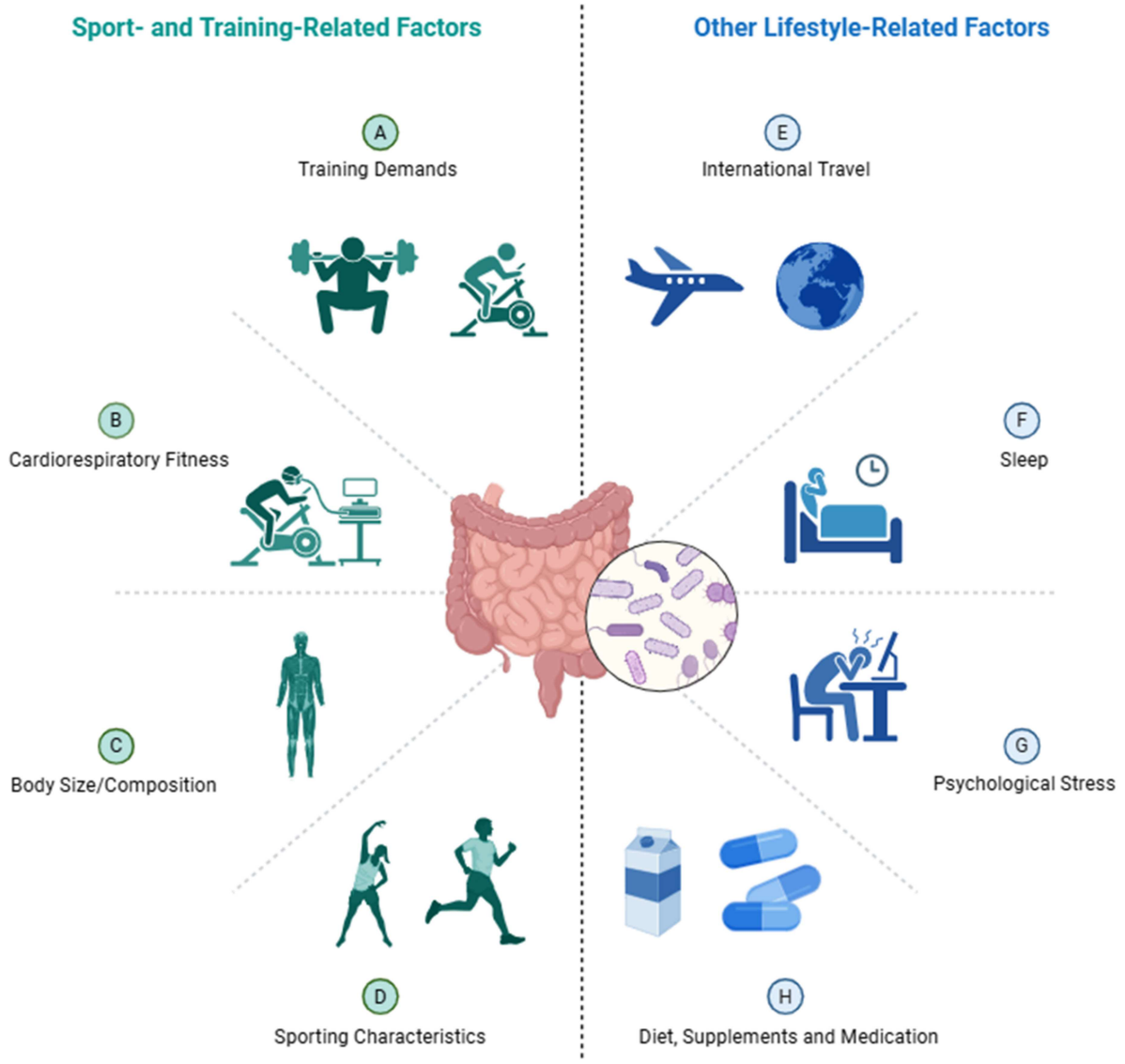


Figure 1. Factors affecting the athlete's microbiome, including training demands [30,37], maximal oxygen uptake/cardiorespiratory fitness [29], body size and composition [25], sporting characteristics [28], international travel [36], psychological stress [16], sleep [232], and dietary intake/supplement use [233].

Probiotics and Prebiotics (ISAPP) is "a substrate that is selectively utilized by host microorganisms conferring a health benefit" [42]. The Global Prebiotic Association (GPA) provide a similar definition, but place less of an emphasis on selective utilization, and extend it to include performance benefits: "a product or ingredient that is utilized in the microbiota, producing a health or performance benefit" [43]. The most extensively researched dietary prebiotics are non-digestible fructans and galactans [42,44] and examples of different prebiotics, along with their primary sources and effects on the gut microbiome/metabolome are summarized in Table 1.

Most of the compounds identified as prebiotics fall under the definition of dietary fiber, although not all types of dietary fiber exhibit prebiotic properties. Of the candidate prebiotic types presented in Table 1, only polyunsaturated fatty acids (PUFAs) and phenolics/phytochemicals would not be classed as dietary fiber. Most recognized prebiotic substrates, such as inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS) [94], and other oligosaccharides, are soluble prebiotic fibers, whereas resistant starches, and some mannans, resist digestion in the small intestine, and therefore represent examples of prebiotics with insoluble-type characteristics [95,96]. Soluble fibers are characterized by their ability to disperse or dissolve

Table 1. Prebiotic types, dietary sources, and reported changes in the gut microbiome and metabolome.

Carbohydrate-based prebiotics		
Prebiotic type	Example sources	Primary gut microbiome/metabolome changes
Inulin	Roots and tubers (e.g. Jerusalem artichoke, yacon, chicory roots, dahlia tubers), vegetables (e.g. leek, asparagus, garlic, onion), fruits (e.g. banana) and grains (e.g. wheat) [45]	↑ *Bifidobacterium, Anaerostipes, Faecalibacterium, and Lactobacillus* [46] ↓ *Bacteroides* [46] ↑ fecal acetate, isobutyrate and total SCFA content [47], although this effect is not consistently reported in human studies [46]
β-glucans	A form of dietary fiber made exclusively of glucose units connected through β-glycosidic bonds. They are abundant in the extracellular polysaccharides found in microorganisms and are key components of the cell walls of cereals, fungi and algae [48]. The main types of beta-glucans are cereal β-glucans (from oats and barley), yeast β-glucans (YBGs), mushroom β-glucans, and less commonly bacterial or algal β-glucans [49]	↑ *Bacteroides* [50,51], *Bifidobacterium* (*B. longum*) [52], *Haemophilus*, *Veillonella* and *Sutterella* [51] ↓ *Firmicutes* (Streptococcus) [50], ↓ *Firmicutes:Bacteroidetes* ratio [50,52] Contrasting evidence shows no changes to the gut microbiome following YBG supplementation [53] ↑ plasma acetate and butyrate with cereal β-glucan [51], but human data examining YBG supplementation currently shows no effect [53]
Galactooligosaccharides (GOS)	Mainly produced by the hydrolysis of lactose or whey [54]	↑ *Bifidobacterium* [55–61], *Lactobacillus* and *Clostridium* coccoides-*Eubacterium* rectale group [55] ↓ *Bacteroides*, *C. histolyticum* group, *Desulfovibrio* [55] ↑ plasma acetate and total SCFAs [62]
Fructooligosaccharides (FOS)	Occur naturally in some vegetables, such as onion, leek, chicory, wheat, rye, yacon, garlic, artichoke, tomatoes, asparagus and bananas [63,64] However, extraction from foods is difficult, meaning it is often produced from sucrose or inulin by microbial enzymes [65,66]	↑ *Bifidobacterium* [63], *Lactobacillus* [67] ↓ *Phascolarctobacterium* [68], *Bacteroides*, *clostridium*, and *fusobacterium* [69,70] ↑ fecal SCFAs, particularly acetate and propionate [70]
Mannanoligosaccharides (MOS) and mannan-based polysaccharides	Mainly produced by the enzymatic hydrolysis of mannans from plant-based substrates such as locust bean gum, guar gum, konjac glucomannan, and agro-industrial wastes [71]	There is little human data specifically looking at MOS; however, animal data indicates the following effects: ↑ *Bacteroides* (*B. ovatus*), *Lactobacillus* [72,73] ↓ *Firmicutes, Proteobacteria* [72,73] ↑ cecal butyrate [72] However, Yeast Mannans have been studied in humans, with the following changes observed: ↑ *Bacteroides (B. thetaiotaomicron* and *B. ovatus)* [74,75] ↑ fecal propionate [74]
Xylooligosaccharides (XOS)	Mostly obtained from hemicellulose-rich agro-industrial residues, such as corn cob, wheat straw, sugarcane bagasse, and rice husk, with pretreatments often used prior to enzymatic hydrolysis [76]	↑ *Bifidobacterium* [77–79], *Lactobacillus* [78], though increased *Lactobacillus* is not consistently reported [77], *Blautia* (*B. hydrogenotrophica*), *Anaerotruncus*, *Dialister*, *Oscillospira* [80] ↓ *Clostridium* (*C. perfringens*) [78], *Eubacterium*, *Subdoligranulum*, *Streptococcus*, *Howardella*, *Slackia* [80] Only human fecal SCFA data shows no change [79]
Human milk oligosaccharides (HMOs)	HMOs are the third most abundant solid compound found in human breast milk [81]. Some HMOs can also be produced industrially, either through bacterial fermentation or via enzymatic conversion [82]	↑ *Bifidobacterium* (*B. adolescentis*, *B. longum*), *Faecalibacterium* (F. *prausnitzii*), *Anaerotruncus* (*A. colihominis*), *Pseudoflavonifractor* and *Prevotella* [82] ↓ *Lachnospiraceae* (family level), *Dorea* [83], *Firmicutes* and *Proteobacteria* (Phylum level) [84]
Non-carbohydrate based prebiotics		
Prebiotic type	Example sources	Primary gut microbiome/metabolome changes
Polyunsaturated fatty acids (PUFAs)	Split into two families: OMEGA-3 and OMEGA-6 fatty acids. Found in high quantities in certain nuts (e.g. walnuts), fish (e.g. salmon, cod), seeds (e.g. chia, flaxseed), plant foods (e.g. seaweed, avocado), meats (e.g. beef) and oils (e.g. olive) [85,86], but can also be extracted into supplemental forms [87]	↑ *Coprococcus* and *Bacteroides* [88] ↓ *Collinsella* [88] ↑ serum iso-butyrate and isovalerate [88]
Phytochemicals and phenolics	Occur naturally in many fruits and vegetables and cereals. Also found in tea, beetroot, coffee, wine, dark chocolate, and cacao powder [89]. Can also be isolated into concentrated supplements or extracts, which can be consumed in capsule form, in	Human polyphenol data is currently limited to red wine polyphenols, which demonstrate: ↑ *Bifidobacterium, Lactobacillus, Enterococcus*, *Eggerthella* (*E. lenta*), *Faecalibacterium* (F. *prausnitzii*) and *Roseburia* [91,92] ↓ *Escherichia* (*E. coli*) and *Enterobacter* (*E. cloacae*)

Table 1. (*Continued*)

Carbohydrate-based prebiotics		
Prebiotic type	Example sources	Primary gut microbiome/metabolome changes
	concentrated juices or powders, in yogurt-soluble forms, or incorporated within snacks and canned products [90]	[92] Emerging evidence that polyphenols from tart cherries can alter the abundance of certain gut microbial species, but this effect may be modulated by baseline *Bacteroides* levels [93] Rodent studies also indicate that phenolic compounds generally increase *Bifidobacterium, Lactobacillus, Akkermansia, Prevotella*, and *Bacteroides*, while reducing *Firmicutes, Proteobacteria*, and other inflammation-associated taxa [89]

SCFA, short chain fatty acids; YBG, yeast β-glucan; GOS, galactooligosaccharides; FOS, fructooligosaccharides; MOS, mannanoligosaccharides; XOS, xylooligosaccharides; HMOs, human milk oligosaccharides; PUFAs, polyunsaturated fatty acids.

in water, enabling microbial fermentation within the colon [94]. In contrast, insoluble fibers remain intact in aqueous environments and primarily contribute to fecal bulk and speed up intestinal transit [97]. In general, most soluble fibers are much more readily and quickly fermented by gut microbes when compared to insoluble dietary fibers [94,98]. Additionally, by accelerating movement through the GI tract, insoluble fiber reduces the total time available for microbial fermentation of undigested substrates within the colon [99]. However, insoluble dietary fiber does still play an important role in promoting gut microbial diversity via fermentation, since some insoluble dietary fibers, such as resistant starch, can be fermented by gut microbes at varied rates, and to different extents [98,100].

1.3 Introducing the potential benefits of prebiotics for athletes

Given prebiotics' ability to promote gut microbial diversity, and the impact that microbial diversity can have on immune function [101], gut barrier integrity [102] and systemic inflammation [103], prebiotics present a potential intervention to reduce both URS and GIS during periods of high stress or training load. Indeed, it has been suggested that athletes should prioritize nutritional strategies that "fuel their microbes" [104], in order to promote improved health and performance. The microbial metabolism of ingested prebiotics and other dietary fibers in the gut generates short-chain fatty acids (SCFAs) [105], which are low-molecular weight (1–5 carbon atoms) aliphatic carboxylic acids [106]. Butyrate, acetate and propionate are the three primary SCFAs produced within the gut, and are thought to be primary mediators of the health-promoting effects associated with a more favorable gut microbiome composition [107]. Despite limited experimental evidence in humans, increased SCFA production has been proposed to benefit athlete health and performance by reducing URS risk, attenuating the inflammatory response associated with exercise-induced muscle damage and modulating energy production and substrate utilization [108]. Given that prebiotic intake can increase SCFA concentrations [105], prebiotics present an intervention to upregulate the beneficial physiological effects of SCFAs and potentially improve athlete health and performance. However, athletes have elevated levels of fecal SCFAs compared to sedentary controls [26], and it remains unclear whether further increases in SCFA production or availability could provide additional health or performance benefits.

Prebiotic intervention studies in athletic cohorts to date demonstrate an increased abundance of *Bifidobacterium* spp. [109] and a decreased frequency and severity of URS and GIS [110,111]. Prebiotics have also been shown to increase sIgA secretion [110,111] and reduce biomarkers of systemic inflammation [112], intestinal epithelial injury [111,113] and bone resorption [109] in athletes, highlighting their potential to improve immune function, gut integrity, inflammatory responses and bone health. Athletes may benefit most from prebiotics during periods when alpha diversity declines, such as with international travel or heavy training loads. While recognizing that evidence in this field is emerging but remains limited, this review aims to evaluate current research on prebiotics in the context of sport and exercise, including potential benefits that remain untested in athletes. Future research directions are also explored, as well as practical recommendations for practitioners considering the use of prebiotics with athletes.

2. Evidence synthesis: prebiotic supplementation in athletes

2.1 Outcomes supported by current evidence

2.1.1 The effect of prebiotics on exercise-induced gastrointestinal syndrome and gastrointestinal symptoms

Exercise-induced Gastrointestinal Syndrome (EIGS) refers to changes in gastrointestinal integrity and function in response to exercise, that can result in GIS [114–116]. Exercise-associated GIS can have a multitude of negative effects on athletic performance including reduced exercise intensity/power output, or even discontinuation of activity, if severe enough [117,118]. The frequency of the occurrence of GIS in athletes ranges substantially depending upon the context and the measurement methods used. A previous review article stated that 30%–50% of athletes experience GIS during maximal intensity endurance exercise [119], but more recent data from endurance sports indicates that the proportion of athletes experiencing GIS ranges from <5% to >90% across different events and populations [117]. Whilst exercise-associated GIS are often quantified using modified visual analogue scales [120], acute perturbations to the gut barrier integrity during exercise are commonly assessed using measures of intestinal permeability, such as the urinary ratio of non-digestible sugars, or via measuring indirect markers of intestinal epithelial injury in the circulation [121]. One of the most widely measured markers of intestinal epithelial injury is intestinal fatty acid-binding protein (I-FABP). I-FABP has been consistently shown to increase following acute exercise, with this response being augmented in hot environments [121]. However, although transient increases in I-FABP are indicative of acute intestinal epithelial injury, they should not necessarily be interpreted as a risk factor for long-term intestinal damage. In fact, regular exercise may even promote adaptations that strengthen the gut barrier, aligned with the concept of exercise-induced hormesis [11].

Research into the efficacy of biotics on EIGS has primarily focused on probiotics and synbiotics [122]. Work by Rauch et al. (2025) suggests that a daily prebiotic blend (16 g·day^{-1}) comprising soluble fibers including partially hydrolyzed guar gum (2.56 g), resistant starch, and β-GOS (3.68 g) may modestly attenuate exercise-induced impairments in intestinal integrity [113]. The study demonstrated that the prebiotic blend reduced exercise-induced epithelial injury in response to 3 h of running at 60% of maximal oxygen uptake ($\dot{V}O_{2max}$) in 30 °C, as demonstrated by a reduction in the magnitude of increase in I-FABP. A second key finding was the lower soluble CD14, a circulating endotoxin-related marker, following supplementation. Importantly, these benefits occurred without adverse effects on gastrointestinal transit time, suggesting that prebiotics may help stabilize the gut barrier under exertional heat stress. Building on this seminal finding, evidence from Parker et al. (2026) demonstrated that prebiotic β-GOS may support gut barrier function during exercise-heat stress through a proof-of-concept randomized controlled trial [111]. The study examined six weeks of daily β-GOS (2.8 g·day^{-1} of active GOS) in 26 healthy male athletes undertaking a simulated football match performed in hot conditions (33 °C and 50% relative humidity). The prebiotic intervention resulted in a 35% attenuation in the peak change in I-FABP. Other studies assessing intestinal barrier integrity in response to exercise stress utilize probiotic or synbiotic supplementation (see review by Rauch et al. [122]), limiting the ability to draw conclusions regarding the ability of prebiotics alone to attenuate gut barrier disturbances, and highlighting the need for further studies.

Prebiotics may also alleviate GIS that occur in response to strenuous exercise. In the study by Parker et al. (2026), athletes receiving β-GOS also experienced lower GIS severity both at rest and during exercise, suggesting enhanced GI tolerance to physiological heat stress [111]. Another important study that highlights the potential for prebiotic supplementation to reduce GIS during an intense block of training is Parker et al. [110]. Thirty-three elite rugby union players were randomly assigned to either a prebiotic (2.8 g·day^{-1} β-GOS) or visual and taste-matched placebo for 24 weeks during the professional season. Compared to those in the placebo group, the participants consuming β-GOS experienced a lower incidence and severity of total and upper GIS over 24 weeks. This highlights that in elite athletes, where training load and physiological stress are high, prebiotic β-GOS can reduce GIS, potentially improving performance and long-term training adaptation. Similar future studies in elite athletes from a variety of sports, including measures of the gut microbiome and SCFAs would strengthen the body of evidence and demonstrate that prebiotics are an effective intervention that can reduce GIS in athletes.

Despite these promising findings, improvements in GI comfort are not consistently reported with prebiotic intake. Additionally, associations between changes in markers of epithelial injury/endotoxin translocation and

exercise-associated GIS are weak, and often non-significant [123], highlighting the complex etiology of EIGS and GIS. Therefore, reductions in epithelial injury driven by prebiotic intake may not always reduce GIS during exercise. The complex interaction between biomarkers of EIGS and GIS is demonstrated in the findings of Rauch et al. (2025), who found that the 16 g·day^{-1} prebiotic mixture did not improve GIS in response to the exertional heat stress, despite the attenuation of intestinal epithelial injury [113]. These findings emphasize the multifaceted nature of GIS, whereby intestinal epithelial injury represents only one of multiple candidate physiological mechanisms (e.g. splanchnic hypoperfusion, reduced gastric emptying, nutritional causes) that may underpin exercise-associated GIS [118].

Another recent pilot-study explored whether 12-week supplementation with a β-GOS could improve GI comfort in recreationally trained endurance athletes versus a maltodextrin placebo [124]. The 2.8 g·day^{-1} of β-GOS did not result in changes in GIS before or after a 20 min run at 80% $\dot{V}O_{2max}$. However, the relatively low cardiorespiratory fitness and training load of the recreationally active participants (mean $\dot{V}O_{2max}$ 43.9 ± 6.7 ml·kg^{-1}·min^{-1}; training only twice per week), combined with the low baseline GIS (overall gut discomfort 1 ± 3 out of 10), likely limited the potential for observable improvements following prebiotic supplementation. In addition, the small sample size ($n = 9$ per group) would have limited the statistical power to detect between-group differences. The absence of microbiome, metabolomic, and GI integrity markers further constrains the interpretation of these findings. Future studies should aim to determine how differences in pre-intervention gut microbial composition, gut barrier integrity or history of GIS modulate the efficacy of prebiotics, to move towards personalized prescription.

2.1.2 Prebiotics and athlete immunity

Emerging evidence on how prebiotics may support athlete immunity was demonstrated by Parker et al. (2023), where 33 elite rugby union players consumed either β-GOS (2.8 g·day^{-1}) or a placebo daily for 24 weeks [110]. Compared to those in the placebo group, participants receiving β-GOS reported a shorter duration of URS (−2 days) and demonstrated a 42% increase in sIgA secretion rate. This highlights that in elite athletes, who experience high physiological and psychological stress during competition periods, prebiotic supplementation can reduce training absence, potentially improving long-term training adaptation and therefore performance. Similar future studies in elite athletes from a variety of sports, including measures of the gut microbiome and SCFAs, would strengthen the evidence around the efficacy of prebiotics to enhance immune responses.

A follow-up study by Parker et al. (2026) similarly demonstrated that a dietary prebiotic (2.8 g·day^{-1} of active β-GOS) could elicit meaningful reductions in illness incidence and burden over a 6-week intervention [111]. URS episodes in the β-GOS group lasted an average of 3.2 days, compared with 8.9 days in the placebo group, and overall symptom severity was nearly three-fold lower. An improved mucosal immune response was again evident, as sIgA concentrations increased following exercise in the β-GOS condition but declined in the placebo group. Collectively, these findings indicate that targeted GOS supplementation may offer a practical strategy to reduce URS burden and support immune defense during periods of environmental and physiological stress in athletes.

As well as GOS, research indicates that β-glucans (a class of functional polysaccharides with reported prebiotic effects; Table 1), may also be effective at reducing URS in athletic cohorts. Yeast β-glucan (YBG) is an example of a β-glucan, and is seen as a high-specificity dietary fiber, due to the few gut bacteria that are able to use YBG as a substrate [125]. Talbott et al. (2009) compared self-reported URS in three groups of athletes, who consumed one of three daily supplementation strategies in the four-week period following a marathon: 250 mg·day^{-1} of yeast-derived beta 1,3/1,6 glucan (Wellmune WGP®), 500 mg·day^{-1} of yeast-derived beta 1,3/1,6 glucan (Wellmune WGP®) or a placebo (rice-flour capsules) [126]. The two β-glucan groups experienced a significant reduction in URS at both 2 and 4 weeks, with only 8% of subjects in both treatment groups experiencing URS at 4 weeks, versus 24% in the placebo group. The lack of microbiome or metabolomic measures make it difficult to determine if these effects were attributable to fermentation of YBG in the gut, or alternative mechanisms.

Conflicting data does exist [127], with 2-weeks of oat β-glucan supplementation (5.6 g·day^{-1}) unable to alter URS incidence in the two-week period following a 3-day intense training block (3 h cycling per day at ~57% of peak power output). A variety of immune system biomarkers were measured, but there were no differences at rest or post-exercise. These discordant findings could be due to the source of β-glucans (yeast

vs oat), the different exercise stressors (marathon race vs 3 days of intense cycling training) and the length of supplementation protocols (2 weeks vs 4 weeks). Additionally, Nieman et al. provided the final dose of oat β-glucan the day after the final day of cycling training and continued to measure URS incidence for the subsequent two weeks. Given the ability for gut microbiota and markers of immunity to change rapidly in response to dietary and lifestyle changes, perhaps any benefit of the β-glucan will have diminished after supplementation ceased. It could be hypothesized that had supplementation continued throughout the two-week period, URS incidence may have differed between groups.

Additionally, the results of the Nieman et al. (2008) and the Talbott et al. (2009) studies may not be directly comparable due to the different types of β-glucan given to participants. YBGs, such as the β-(1 → 3)/(1 → 6)-glucan used by Talbott et al. (2009), differ structurally from cereal β-glucans, such as oat β-glucan, which predominantly contain β-(1 → 3)/(1 → 4) linkages [128]. These structural differences also influence the physiological responses that occur. YBGs exert effects through both prebiotic and direct immunomodulatory mechanisms [129], whereas OBG is primarily considered a fermentable dietary fiber with potential prebiotic effects [49]. Consequently, the doses used across studies (250–500 mg·day^{-1} YBG vs 5.6 g·day^{-1} OBG) are not directly comparable and should not be interpreted as a simple dose-response relationship.

Overall, there is some preliminary evidence to indicate that certain prebiotics (GOS, YBGs) can reduce the incidence of URS and increase sIgA secretion rate in sporting contexts. However, much more research is required to determine how prebiotic type, dose, supplementation length, and sporting demands may influence outcomes, together with mechanistic insights.

2.2 Outcomes with emerging evidence

2.2.1 The potential for prebiotics to augment physiological adaptations to training and accelerate recovery

Some insights into the potential for prebiotics to augment training adaptations may be gained through the randomized controlled trial by Williams et al. (2022), who examined the effects of 12 g·day^{-1} of FOS-enriched inulin intake during six-weeks of supervised high-intensity interval training (HIIT) in sedentary participants [130]. Despite not improving $\dot{V}O_{2peak}$, FOS-enriched inulin alongside HIIT increased the relative abundance of *Bifidobacterium* taxa (38-fold greater change compared to placebo), upregulated several metabolic pathways involved in substrate utilization and energy metabolism, and elicited greater improvements in ventilatory thresholds. Total SCFAs also increased in the inulin group, and decreased in the placebo group, but these differences were not statistically significant. Future research should determine if prebiotics can also elicit similar responses to structured exercise in trained endurance athletes, especially given that the ventilatory thresholds, particularly the second ventilatory threshold, may be a stronger predictor of endurance performance when compared to $\dot{V}O_{2peak}$/$\dot{V}O_{2max}$[131,132]. Interestingly, greater improvements in $\dot{V}O_{2peak}$ in response to HIIT were associated with a greater abundance of gellan-degrading pathways, the *Bacteroides_A* genus, and the *B. uniformis* species. While these findings suggest that gut microbial composition could potentially modulate physiological responses to exercise, it remains unclear whether this would impact upon the effectiveness of prebiotic supplementation to support training adaptation, particularly in well-trained athletes.

Further insights into prebiotic mediated effects on adaptations to exercise have emerged from research on β-glucans, particularly YBG. First, Wang et al. (2020) provided *in vitro* evidence that YBG has prebiotic effects, in that it remains undigested through the upper gastrointestinal tract but is efficiently fermented by gut microbiota in the colon [133]. Using *in vitro* simulated human digestion and microbial fermentation, their results indicated that YBG led to similar beneficial shifts in microbial composition to inulin, including reduced *Firmicutes:Bacteroidetes* ratio and enhanced growth of *Bifidobacterium*, particularly *B. longum*. Subsequently, Wang et al. (2022) demonstrated that four weeks of supplementation with 2 g·day^{-1} of β-glucan improved grip strength and $\dot{V}O_{2max}$ in trained athletes (professional table tennis players) when compared to pre-intervention levels, with these improvements not being evident in the control group [52]. These functional improvements were accompanied by lower concentrations of tumor necrosis factor α (TNF-α) and changes to the plasma metabolome that may be indicative of increased creatine metabolism, potentially explaining the observed improvements in grip strength.

Given the interconnectedness of the gut and systemic immune responses [134], prebiotics ability to alter the gut environment may influence the intestinal immune environment and the intestinal barrier integrity, potentially altering the levels of endotoxemia and systemic inflammation. Zabriskie et al. (2020) investigated the impact of YBG intake (250 mg·day^{-1} for 13 days) on inflammatory responses in healthy, active participants, when compared to a maltodextrin placebo, as part of a double-blind, crossover trial. Ingestion of YBG resulted in reductions in macrophage inflammatory protein 1β, a circulating pro-inflammatory cytokine, following strenuous treadmill exercise at 55% of $\dot{V}O_{2peak}$ in a hot and humid environment [135]. This anti-inflammatory response occurred alongside perceptual responses indicative of improved perceived recovery (decreased anger, increased vigor) compared to the placebo group, providing preliminary evidence in support of the hypothesis that prebiotics can potentially reduce post-exercise inflammation and improve recovery via modulation of the gut–immune and the gut–brain axis. Reductions in interleukin 8, monocyte chemoattractant protein-1 and TNF-α also approached statistical significance ($p \leq 0.095$ but >0.05 for all three markers), demonstrating mechanistic potential that warrants further investigation across different prebiotic types, doses and exercise stimuli. Another study by Hadžić et al. (2023) investigated the effects of a four-week 17 g·day^{-1} soluble dietary fiber prebiotic (Nutriose®) on neuromuscular function, cardiovascular endurance and perceived exertion in young basketball players [136]. At the end of the 4-week supplementation period, there were species differences in gut microbial composition – two unidentified species showed significant group differences: an *Intestinibacter* species was higher with maltodextrin, while a *Ruminococcaceae* species was higher with Nutriose® fiber. There was also a significant reduction in rating of perceived exertion during training and competition in the soluble fiber group compared to placebo, however this did not translate to any improvements in neuromuscular function or cardiovascular fitness measures. Therefore, these findings suggest that prebiotics may not augment exercise adaptation in all contexts, but the relatively small sample size and the lack of methodological detail as to how the physiological/fitness tests were performed limit the interpretation of these findings.

Collectively, these studies provide some preliminary evidence that prebiotic interventions, particularly inulin-type fructans and β-glucans, may enhance exercise adaptation and potentially accelerate recovery. The underlying mechanisms of these improved physiological adaptations appear to be increased abundance of beneficial microbial taxa, greater production of SCFAs and other beneficial metabolites, and reduced inflammatory responses to exercise. However, the evidence to date relies mainly on poorly controlled studies in small samples, or examined sedentary subjects, meaning that more placebo-controlled studies examining the effects of different prebiotics in well trained athletes across a variety of sports are warranted. Future work should also aim to elucidate the mechanistic basis for any exercise adaptation or recovery benefits, together with how training status, intervention duration, and individual differences in gut microbial diversity impact the efficacy of prebiotics.

2.2.2 Prebiotics to support sleep

The role of prebiotics to support sleep has been explored by Gough et al. (2025). They explored whether 12-week supplementation with a β-GOS prebiotic (2.8 g·day^{-1}) could improve subjective sleep, via a core consensus sleep diary, in recreationally trained endurance athletes, when compared to a maltodextrin placebo [124]. The prebiotic β-GOS supplement was unable to produce significant improvements in any of the sleep-based measures over the 12 weeks. However, the small sample size ($n = 9$ per group) and the absence of an a-priori power calculation also likely limited the statistical power to detect differences in sleep between these groups. The lack of microbiome, metabolome and gut barrier integrity measures also limits the mechanistic interpretation of their findings.

Despite the lack of evidence in athletes, some studies in non-athletic cohorts indicate that prebiotics can improve sleep. Tanihiro et al. (2024) demonstrated the potential for 1.1 g·day^{-1} of yeast mannans (YMs; introduced in Table 1), to improve sleep quality [74]. After four weeks, the YM group showed a significant increase in the duration of non-REM sleep stage 3 (N3) compared with placebo. Across the trial, YM intake also extended total time in bed and reduced the time required to enter N3 relative to placebo. Stepwise linear regression analysis of metabolomic markers indicated that changes in fecal propionate were the primary factor explaining changes in total time in bed and changes in fecal gamma-aminobutyric acid were the main metabolomic change explaining changes in non-REM sleep duration. This data provides some preliminary evidence that changes in the gut metabolome resulting from prebiotic supplementation may

be key changes driving improvements in sleep quality, but it remains unclear whether athletes would experience similar beneficial effects.

Looijesteijn et al. (2024) examined the effects of a three-week intervention with either 1.3 g or 2.0 g per day of GOS on gut microbial composition and perceived sleep quality, using the Athens Insomnia Scale [61] in healthy women (42–70 years, BMI 18.7–30 $kg{\cdot}m^{-2}$). Significant increases in *Bifidobacterium* were found for both doses, and a shift in the overall microbiota composition was found with the 2.0 $g{\cdot}d^{-1}$ dose. Despite these changes in the gut microbiota, no significant effects were found on sleep quality, although changes in sleep quality did approach statistical significance for the 1.3 $g{\cdot}d^{-1}$ dose ($p = 0.09$). However, although the study included 44 participants per treatment group based on an a-priori power calculation (80% power, effect size = 0.3), the authors acknowledged that the study was not specifically powered to detect changes in secondary outcome measures such as sleep. Future studies that include sleep as their primary outcome measure are therefore warranted, ideally being adequately powered to detect at least a moderate effect size (e.g. Cohen's $d \geq \sim 0.5$).

Overall, there is a lack of evidence, particularly in highly active populations or athletes, to determine whether prebiotics can improve sleep quality and duration, or attenuate sleep disruptions during periods of high stress such as competition. However, rodent data demonstrate improved sleep with prebiotics [137,138], and theoretical mechanistic work [139–141] and observational studies [142] also link dietary fiber, and/or alterations in the gut microbiome with better sleep. Therefore, if more high-quality studies are conducted, which combine both objective and subjective measures of sleep quality, then perhaps specific prebiotic fibers will demonstrate sleep-enhancing effects in sporting contexts.

2.2.3 Prebiotics to support wellness, mood and cognitive function in athletes

Given the bidirectional communication between the enteric and central nervous system, termed the "gut–brain axis" [143], interventions that can modulate the gut microbiota and overall GI function, such as prebiotics, may have consequent implications for psychological state and higher cognitive functions. Evidence indicates that athletes are susceptible to a variety of mental health issues, which may stem from both sport-related factors (such as injury, overtraining, and burnout) and external factors [144]. Periods of high/increased training load can also result in mood disturbances and reduced subjective wellbeing [145,146]. Therefore, interventions that can promote improved mental wellbeing and prevent or attenuate mood disturbances are warranted.

Gough et al. (2025) compared 12 weeks of β-GOS supplementation to a maltodextrin placebo and included assessments of subjective psychological wellbeing [124]. Although no significant group-level effects were observed, some subjective wellbeing measures showed promising trends. More participants in the β-GOS group achieved clinically meaningful improvements in Warwick-Edinburgh Mental Wellbeing Scale score (≥3 points) compared with placebo (6 vs 2), suggesting potential benefits in certain individuals. However, substantial inter-individual variability was evident, with random effects accounting for 73% of the variance, which may explain the lack of significant overall effects despite meaningful improvements in some participants. The authors concluded that longer trials, with larger sample sizes are required to clarify the effects of prebiotic supplementation on general wellbeing.

Additionally, the work of Talbott et al. (2009) provides evidence that β-glucan supplementation can improve mood in athletes, with participants reporting higher vigor and lower levels of tension, fatigue, confusion, and anger based on a profile of mood state survey, in the four week period following a marathon, when consuming a prebiotic [126]. There is also some evidence that prebiotics may reduce anxiety symptoms, particularly in IBS patients [57,147]. Prebiotics may also acutely increase feelings of happiness [148], and reduce focus/attention on negative stimuli compared to positive cues [149]. However, overall meta-analytic estimates indicate that based on the limited number of current studies, prebiotics do not differ from placebo at reducing anxiety and depression [150].

Cognitive function is another factor that can be critical in some sporting contexts [151], particularly in sports where athletes are making rapid decisions to constantly changing external stimuli [152]. Although there are currently no studies in athletic populations, preliminary evidence suggests that prebiotic supplementation can improve cognitive function in healthy adults [153]. Ni Lochlainn et al. (2024) provides some strong preliminary evidence that prebiotics may influence cognitive function. Recruited twins were each randomly allocated to one arm of the study, helping to control for shared genetic and early-life

environmental influences between participants [154]. Participants received a standardized branched-chain amino acid protein powder with either 7.5 g of prebiotic powder (intervention arm; Darmocare Pre®, consisting of ≥3.375 g inulin and ≥3.488 g of FOS) or 7.5 g of maltodextrin powder (placebo arm). Performance on Cambridge Neuropsychological Test Automated Battery (CANTAB) tasks assessing executive function and memory (spatial span, pattern recognition memory, and paired associates learning) significantly improved following the prebiotic intervention when compared to the placebo. Acute ingestion of 5 g of oligofructose-enriched inulin supplementation also appears to improve performance across memory recognition and recall assessments [148]. However, it is unclear how this extends to prolonged supplementation, and whether this is modulated through the gut microbiome, or an alternative mechanism such as altered glucose metabolism. Other promising data also indicates that a variety of probiotic supplementation interventions can improve cognitive performance in healthy individuals [153], providing more evidence that manipulating gut microbial composition may have downstream consequences for brain executive function. Despite this, there is currently no data examining the effect of prebiotic supplementation or other gut microbial manipulations on cognitive function in sporting contexts, or athletic populations. It therefore remains unclear how these promising results in ageing cohorts extend to highly active, younger participants, warranting further research in this area.

2.2.4 Prebiotics to support athlete health during travel—traveler's diarrhea

Traveler's diarrhea (TD) is defined as 4–5 loose bowel movements within 24 h, usually lasting 2–3 days, and often occurring alongside at least one other GIS, for example abdominal discomfort, nausea, vomiting, fever, or blood/mucus in the stool [155]. TD is the most common illness experienced by individuals travelling to developing regions [156]. Of those travelling to developing countries, around 20%–50% appear to develop TD [157]. Each year, the condition is thought to affect over 11 million individuals worldwide [158], with similar incidence (30%–60%) appearing to occur among athletic populations as in the general population [159].

Most cases of TD are caused by exposure to pathogens, with *E. coli* found in the stool of 16%–42% of TD cases, depending upon the region [160]. The reductions in alpha diversity which have been observed in athletes following international travel to competitions [36] may also influence the development of TD. Typically, anti-diarrheal medications and antibiotics are used to help treat TD, but these medications are known to alter gut microbiota composition [158,161]. Therefore, alternative strategies to help prevent TD are warranted. Prebiotics' selective stimulation of beneficial gut bacteria [162] may provide potential anti-pathogenic properties, making them a potential treatment/prevention tool for TD and other travel-related GIS.

Currently, there are no research studies that test the efficacy of prebiotics on TD in an athletic cohort. However, one key study in healthy adults suggests that prebiotics present a potential intervention to reduce the incidence of TD [158]. All participants were travelling to and residing in a country with either low (South Africa, Turkey, the Caribbean Islands) or high (Africa, Asia, the Middle East, Central and South America, Mexico) risk of TD for 14–60 days. Once enrolled, participants were randomized to receive either 5.5 g·day^{-1} of β-GOS (Bimuno®; 2.64 g GOS per 5.5 g serving) or a maltodextrin placebo. Participants began supplementation 7 days prior to travel and continued consuming the treatment until their holiday ended.

Outcome measures included bowel movement frequency, stool consistency, diarrhea incidence and the incidence/severity of several GIS (bloating, vomiting, flatulence and abdominal pain) and the World Health Organization Quality of Life questionnaire. The β-GOS intervention prevented the increase in the number of bowel movements and the increase in abdominal pain from pre-holiday levels that occurred in the placebo group. The prebiotic intervention also significantly reduced the incidence (23% vs 38%) and duration (2.4 days vs 4.6 days) of diarrhea when compared to the placebo group. The abdominal pain associated with diarrhea was also reduced with β-GOS ingestion, with these findings collectively indicating that prebiotics, in particular GOS, are a promising intervention to minimize the TD and other GI disturbances associated with international travel. Prebiotics therefore show potential for athletes who struggle with TD or other GIS during international travel to training camps and/or competition. However, it remains unclear whether these findings extend to elite athletes who have distinct gut microbial composition, dietary habits and psychological stress levels compared to the general population.

2.3 Outcomes with theoretical rationale for beneficial effects but limited experimental evidence in athletes

2.3.1 Prebiotics and exercise performance

Improving athlete health via dietary prebiotics may indirectly improve performance, however, to date there is limited evidence of direct ergogenic benefit from dietary prebiotics. One study explored whether acute supplementation with 15 g of chicory root inulin could improve 15 km cycling time-trial performance versus a maltodextrin placebo [163]. The authors hypothesized that a single 15 g dose of inulin would improve performance in a 15 km cycling time trial by increasing acetate production, which in turn would enhance muscle oxygenation via improved perfusion. It built upon previous findings from animal models, aiming to provide mechanistic insight into the role of gut-derived acetate in endurance exercise performance. However, there was no difference in plasma acetate, muscle oxygenation, or TT performance between conditions. However, whether chronic supplementation with inulin or other prebiotics may result in a greater magnitude of metabolomic changes, and significant performance improvements, remains unclear. In addition, participants were healthy, but only recreationally active (mean $\dot{V}O_{2max}$ 47 ± 9.8 ml·kg^{-1}·min^{-1}), meaning it also remains unknown whether acute or chronic prebiotic supplementation may improve performance in trained endurance athletes, who would likely be capable of producing more reliable all-out time-trial efforts over repeated testing sessions. Alternative dosing strategies or prebiotic types (see Table 1) may also elicit significant improvements in plasma SCFAs, which the acute dose of 15 g inulin was unable to achieve.

2.3.2 Prebiotics and bone health

A pilot study by Ishizu et al. (2021), examined the responses of 29 Japanese female athletes aged 18–25 years to the consumption of one pack of inulin (2.5 g) and lactulose (1.0 g)-fortified prebiotic food per day on top of their habitual diet for 12 weeks [109]. Key findings included a ~6% increased abundance of *Bifidobacterium* spp. at both 3 and 4 weeks when compared to pre-intervention levels. A second important observation was a ~15% reduction in serum TRACP-5b, a biomarker that indicates osteoclast number and bone resorption rate, with low diurnal variability [164]. The serum TRACP-5b level was significantly decreased at 12 weeks compared to pre-intervention levels. A reduction in serum TRACP-5b indicates reduced osteoclast activity and decreased bone turnover, potentially indicating reduced risk of stress fractures, particularly in female athletes, who show significant increases in serum TRACP-5b with stress fracture incidence [165,166]. Indeed, these changes in bone metabolism following prebiotic intake have some theoretical basis, with alterations in the "gut–bone axis", with the metabolites produced via fermentation, such as SCFAs, potentially able to modulate bone metabolism, possibly via influencing regulatory T-cell (Treg) development [167–170]. However, the lack of a control/placebo group in this pilot study make it difficult to determine whether the observed changes in *Bifidobacterium* spp. and bone metabolism markers can be attributed solely to the fortified prebiotic food. Future human research should measure changes in bone turnover markers in adequately powered, placebo-controlled trials, to better determine the impact of dietary biotic interventions on bone health in athletic populations.

2.3.3 Prebiotics to support nutrient absorption

One area with potential theoretical rationale, but little-to-no human data is the potential for prebiotics to increase macronutrient and/or micronutrient absorption. *In vitro* evidence from Caco-2 cells indicates that commercially available prebiotics can up-regulate genes associated with digestion and absorption pathways [171], suggesting a theoretical potential for prebiotics to modulate intestinal epithelial nutrient transport processes, which could affect macronutrient uptake. However, there is no evidence clarifying how these transcriptomic changes extend to humans, nor is there any controlled trials examining the direct effect of prebiotic intake on macronutrient absorption. The existence of registered clinical trials investigating the effects of prebiotic (β-GOS) supplementation on nutrient availability and exogenous carbohydrate oxidation in physically active individuals (ClinicalTrials.gov ID NCT05742516; 185) suggests that more data in this area may be published in the near future. Despite the lack of evidence substantiating a nutrient uptake benefit, it is well established that the increased production of SCFAs can modulate hepatic glucose and lipid metabolism, insulin sensitivity, and hormonal satiety responses [172]. Prebiotics may therefore

indirectly affect whole-body energy metabolism and substrate use via SCFAs, even in the absence of changes in nutrient uptake.

In contrast to the sparsity of evidence around prebiotics and macronutrient absorption, there is a growing body of work indicating that prebiotics can improve micronutrient absorption, in particular minerals such as calcium [173] and iron [174]. With regards to calcium, a nine day intervention with prebiotic lactulose has been shown to increase calcium absorption in a dose-dependent manner in postmenopausal women [175]. Proposed mechanisms for these effects include prebiotic-induced increases in SCFA concentrations subsequently enhancing paracellular uptake via promoting lower colonic pH, which increases calcium solubility [175]. Prebiotics may also support transcellular calcium absorption, as SCFAs can alter calcium transport mechanisms [175]. Given the role of calcium in bone health [176], improvements in calcium bioavailability may be another mechanism by which prebiotics could support bone health.

Iron is another mineral that has demonstrated improved absorption following prebiotic intake. GOS and FOS in particular have been shown to enhance uptake of ferrous fumarate, a widely used oral iron formulation, in particular in populations with compromised baseline iron stores, such as anemic infants and iron-deficient women [174]. Mechanistic bases for enhanced iron uptake are also unclear, but candidate mechanisms include changes in gastric residence time, iron transport protein gene expression, enterocyte proliferation, gut pH, iron solubility and GI or systemic inflammation [174,177]. This could have important implications for athletic cohorts, particularly those at risk of anemia. Both human and rodent data also suggests that prebiotics, particularly inulin-type fructans, may also improve magnesium uptake [178–180], but more research is required to clarify how prebiotics could support the absorption of a wide variety of micronutrients in athletic populations, and the implications for nutrient deficiency, exercise adaptation and illness/injury risk.

3. Practical applications in a sport and exercise setting

Despite the potential beneficial effects of prebiotic supplementation for athletes, current sports nutrition guidelines, such as those from the American College of Sports Medicine (ACSM) [181], or the combined statement from the Academy of Nutrition and Dietetics, Dietitians of Canada, and the ACSM [182], do not mention prebiotics. The recent International Olympic Committee supplementation guidelines for athletic performance introduced probiotics as a potential intervention to reduce URS and TD [183], but also omitted prebiotic supplements. There are also up-to-date Clinical Guide's to Probiotic Products in both the USA and Canada, allowing individuals to see which commercially available products are supported by scientific evidence. However, similar publicly available databases for prebiotic products are absent. The lack of published guidance around prebiotics, particularly in athletic populations, makes it difficult for practitioners to select the optimal type, dose, timing and frequency of prebiotic supplementation. More high-quality published research in athletes is required before guidelines are formally updated, but the remainder of this section will provide some preliminary suggestions and important considerations for practitioners contemplating the use of prebiotics in a sport and exercise context.

3.1 Source and timing of prebiotic intake

Before considering prebiotic supplementation, athletes should prioritize a food first approach, including adequate daily fiber intake and a variety of prebiotic-containing foods, such as garlic, onions, leeks, asparagus, chicory, Jerusalem artichokes, and oats [184]. However, there are limitations associated with consuming prebiotic containing foods, with the main one being the quantity that one would have to consume to achieve a clinically effective dose of prebiotic. For example, the amount of fructan-type prebiotic in 100 g garlic is equivalent to about 14 g inulin [185], meaning that in order to achieve the lowest clinically effective dose of ~2.5 g inulin, one would need to eat ~18 g of garlic (equivalent to ~6 cloves [186]), which is impractical in most scenarios.

Prebiotic supplements therefore provide a more convenient method of consuming an effective dose of prebiotics, particularly during periods of travel and competition, where food choices may be limited for athletes. Long-term prebiotic supplementation could be beneficial in athletes who struggle to consume adequate dietary fiber, as fermentable fibers (which includes most prebiotics), can increase the abundance

of beneficial gut bacteria and increase SCFA production [187], with potential positive downstream effects on GI and immune function. Even for athletes who habitually meet fiber guidelines, adding prebiotic supplements during periods where the risk of URS and GIS is heightened, such as during fixture congestion, intensified training blocks, the winter months, or international travel may be of benefit. When practitioners implement prebiotic intake during these specific periods of high stress/training load, they should consider the time it will take for meaningful prebiotic effects to occur. Gut microbial composition shifts have been detected within a week [188–190], but studies that have found beneficial effects in athletes have often used much longer supplementation periods of at least four weeks [52,110,111,113,126]. Therefore, athletes should ideally begin taking prebiotics at least a week prior to the target period, with longer supplementation windows (≥4 weeks) likely providing an additional buffer to ensure that the intended responses to supplementation have occurred. There is currently no evidence regarding the optimal timing of prebiotic ingestion within a given day or around training and/or competition. Therefore, once supplementation has commenced, consistent daily intake is likely to be much more important than consuming prebiotics at a specific time of day.

3.2 Type and dose of prebiotic

Where prebiotic supplementation is opted for in a sporting context, it should be implemented strategically, and, on a case-by-case basis, with consideration given to type, dose, timing and tolerability. Individual factors such as GI sensitivity, habitual dietary intake, training load, sporting category, commensal gut microbiome composition and sex could all potentially influence the effectiveness of prebiotic intake for a specific athlete. Practitioners should prioritize selection of prebiotic type(s) with more evidence in human randomized controlled trials, which based on studies to date are GOS and inulin-type fructans. Other prebiotic types such as β-glucans show promise with a growing number of studies indicating a potential benefit for active populations, but more evidence is likely required before practitioners can prescribe these with confidence. Providing formal dosage recommendations for athletes is difficult based on the limited current available evidence, but some preliminary dosage suggestions for athletes and practitioners to use are provided below. Currently, the literature does not support personalizing prebiotic doses according to body mass or other physiological or anthropometric characteristics, although this warrants investigation in future studies. The ISAPP do however state that the majority of prebiotics will require a dose of ≥3 g·day^{-1} to have a clinically relevant effect [42], which is a good starting place for practitioners when deciding upon a dose.

More selective prebiotics may achieve clinically relevant effects with doses slightly below 3 g·day^{-1}. Based on previous trials in athletic cohorts, ~2.75 g·day^{-1} of active β-GOS (administered as Bimuno® GOS) appears to be an effective dose to support immunity and promote intestinal barrier integrity [110,111]. However, dose-response studies focusing on gut microbial composition changes in response to high-purity GOS in non-athletic cohorts have found that ≥~5 g·day^{-1} is required to effectively induce bifidogenesis [191,192]. The absence of microbiome measures in previous studies focusing on exercise/athletic contexts [110,111] makes it difficult to explain these discordant findings and determine whether microbiome changes underpinned the altered GI integrity and immune responses. However, β-GOS mixtures produced using enzymes from *B. bifidum* (such as Bimuno® GOS), may have more potent prebiotic and bifidogenic effects than GOS mixtures produced from other sources [193,194], potentially explaining the beneficial effects observed in athletes despite lower doses of active GOS. Therefore, if opting for Bifidobacterium-derived β-GOS mixtures such as Bimuno®, lower doses (≥~1.3 g·day^{-1} active GOS) may still induce prebiotic effects [193,194], particularly for those with greater GI sensitivity. However, given the dose-response nature of the prebiotic effects from Bifidobacterium-derived β-GOS [193], consuming a dose with ≥~2.75 g·day^{-1} of active GOS is preferential and represents an appropriate target dose for most athletes based upon the limited current evidence. Perhaps when using commercially available GOS from other sources, doses of ≥~5 g·day^{-1} may be more appropriate, but in each case instructions from the manufacturer should be followed to minimize adverse effects.

With regards to inulin-type fructans, doses from 3–20 g·day^{-1} have been found to be bifidogenic in human studies [195]; however, previous dose response studies have focused primarily on the 5–10 g·day^{-1} range [196]. Inulin-type fructans can also increase flatulence and abdominal discomfort in some individuals [195], at least in

the initial phases of supplementation, and therefore doses ≤ 10 g·day^{-1} are recommended in most cases, especially in those with a history of GI sensitivity. Other effects of inulin-type fructans, such as increased stool frequency and decreased stool consistency, may require higher doses (≥10 g·day^{-1}) [197] and so if this is a goal from prebiotic supplementation, then higher doses could be trialed in those specific cases.

3.3 Potential side effects and risks

Practitioners should be aware that some athletes may experience a temporary increase in GIS, such as bloating or flatulence, during the initial phase of prebiotic supplementation. It is therefore recommended to closely monitor GI tolerance and side effects and to first trial supplementation during the offseason or preseason period, to determine individual responses before implementing around competition periods. For athletes prone to GI distress, beginning with a lower dose and gradually increasing toward the target intake may improve tolerability. It has been hypothesized that consuming prebiotics in a fasted state may accelerate fermentation rate and therefore increasing the risk of GIS such as bloating [67]. Therefore, despite the lack of current data on prebiotic timing, athletes who experience GIS in response to prebiotics may wish to consider consuming the supplement alongside food. Irrespective of whether athletes choose to take prebiotics with food, consuming prebiotic supplements at the same time each day may help to maximize compliance and promote habitual supplementation as part of a daily routine.

The final consideration for practitioners/athletes considering the implementation of prebiotic supplements in a sporting setting is the manufacturing procedures used for each product, along with the potential for any additional ingredients that could contaminate the supplement, risking bans for elite athletes. When selecting prebiotic products, consideration should extend beyond the quantity of the stated prebiotic ingredient. Practitioners should be familiar with the manufacturing procedures of each product, including how the identity, composition and structural characteristics of the prebiotic are controlled, and whether functional activity is maintained during processing and throughout shelf life. Practitioners should also assess the quality-control procedures utilized in the production of each specific prebiotic, including how raw materials and finished products are tested for consistency, purity and any contaminants [198]. This is important because factors such as degree of polymerization, branching and glycosidic linkages can influence prebiotic functionality, while processing and storage conditions may affect structural integrity. Accordingly, researchers and consumers should consider the specific prebiotic ingredient, dose, evidence supporting prebiotic activity, quality-control procedures, and stability of the ingredient in its final delivery form. For athletes subject to anti-doping regulations, any prebiotic supplement should be independently batch tested and accredited through programs such as Informed Sport to minimize the risk of inadvertent doping.

4. Recommendations for future studies examining prebiotics in athletic populations

Future research aiming to determine the effect of prebiotic supplementation on athletes should aim to follow several key recommendations that will improve the ability to isolate the effect of prebiotics from other extraneous variables and therefore produce improved evidence to inform practice. These recommendations are detailed in Tables 2–4. The specific recommendations that researchers choose to follow will depend upon the hypothesis, context, and variables being tested.

4.1 Supplementation protocol considerations

One of the key considerations around designing studies to test the efficacy of prebiotics in athletic populations is the choice of supplementation protocol. Researchers should prioritize placebo-controlled studies involving prebiotics that have been extensively tested in humans (e.g. inulin and GOS), ensuring adequate length of the supplementation window (≥~2 weeks in most cases) and recording both adherence and any adverse reactions in a systematic manner. Using the dosage recommendations provided in Section 3 and ensuring that at least ~3 g·day^{-1} of prebiotic is provided in most cases, in line with ISAPP guidelines [42], will also help to maximize the chance of observing a meaningful physiological effect. Where

Table 2. Methodological considerations/recommendations relating to the supplementation protocol in prebiotic-based research in athletic populations.

Supplementation protocol recommendations					
Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
Length of intervention	Prescribe properly dosed, daily supplementation protocols for an adequate time period	Two weeks of supplementation appears to be the minimum to elicit beneficial effects [199,200]	Four weeks of supplementation	Six or more weeks of supplementation. Ideally with multiple follow up trials over the supplementation period to elucidate the time course of adaptations and any habituation to prolonged supplementation	Ensuring sufficient length of supplementation maximizes the likelihood that the prebiotic is able to meaningfully alter the participant's physiology prior to follow up laboratory visits
Type of supplement	Use a supplement that has been proven to improve gastrointestinal structure/function in previous human or animal research	Select a prebiotic with established safety in humans, adequate shelf-life and storage stability, a clearly defined dose, and some evidence that it is likely to influence the main outcome(s) while causing minimal side effects	Choose a supplement with prior human evidence, while ensuring good palatability and taste/texture that can be matched to a placebo	Use an informed-sport accredited/batch-tested prebiotic that has been extensively tested in human subjects at the dose given, and that has a clear mechanism of action for each of the primary outcome variables	Maximizes the chance of beneficial effects occurring and minimizes the risk of adverse reactions. Given the lack of current data on prebiotics in athletes, studies should first prioritize prebiotic types with current extensive evidence (e.g. inulin, GOS), before candidate prebiotics are studied
Intake of other supplements	Ensure standardization, or cessation of supplements that may interact with prebiotics	Individuals who habitually use pre- or probiotic supplementation have had at least a 3-month break from supplementation prior to the trial and use of candidate prebiotics (e.g. OMEGA-3, polyphenols) is kept consistent throughout the trial period	Individuals who habitually use other candidate prebiotics such as OMEGA-3 or polyphenol supplements have refrained from using them for at least 3 months prior to commencing participation	All other supplements that are not classed as candidate prebiotics (e.g. vitamins, minerals, antioxidants, creatine, beta alanine) are also monitored and kept consistent throughout the testing periods	Isolates the effect of the study's supplementation regimen from other previous or ongoing supplement use. Even supplements that are not candidate/ emerging prebiotics may still impact performance and physiological responses, despite not directly interacting with prebiotics
Antibiotic use	Ensure antibiotic cessation prior to the trial beginning and carefully monitor for	Minimum 3-month gap between finishing last course of antibiotics and	6-month gap between finishing the last course of antibiotics and starting the trial	9 to 12-month gap between finishing last course of antibiotics and starting the trial,	Antibiotics reduce gut microbial diversity [161], likely cancelling out some of the

Table 2. (*Continued*)

Supplementation protocol recommendations					
Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
	antibiotic use during the trial	starting the trial and immediate exclusion if antibiotics are taken during the trial		since evidence shows that some bacterial species have not recovered back to baseline even after 6 months [201]	beneficial effects of prebiotic supplementation on the gut microbiome
Supplement adherence	Measurement of adherence to the supplementation protocol, with exclusion if a minimum adherence is not met	Minimum of 80% adherence, a threshold previously used to define high/acceptable adherence [202,203], confirmed via packaging return	Minimum of 90% adherence, confirmed via packaging return	≥90% adherence, confirmed via a combination of sachet return, daily intake logs or supervised intake	Ensures that enough of the supplement is consumed to elicit the intended physiological effects
Use of a placebo	Ensure the study design involves consumption of a placebo, either with a control group or via a crossover design with an appropriate washout period	Single blinded trial. Placebos should also be closely matched for appearance, taste and texture, especially in crossover designs	Trial is double blind	Trial is triple blind (i.e. researchers also stay blinded during the data analysis procedure)	Confirms that beneficial effects are resulting from physiological responses to supplementation, as opposed to a placebo/nocebo effect. Double/triple blind trials also minimize researcher bias
Supplement safety data	Ensure any adverse events to supplementation are reported	Retrospective follow up at the end of the supplementation period to determine any side effects that occurred	Weekly check-ins to determine any side effects, together with a method of rating the frequency and intensity of these side effects	Daily check-ins (potentially alongside other daily questionnaires such as URS), to determine any side effects suffered, and their frequency/severity	Helps to clarify the risk:reward ratio of the supplement and helps to determine the frequency and severity of any adverse effects resulting from supplementation

GOS, galactooligosaccharides; URS, upper respiratory symptoms.

Table 3. Recommendations for designing studies and standardizing behavioral, nutritional and physical activity variables across trials in prebiotic focused studies in athletic populations.

Study design/behavioral standardization recommendations

Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
Sample size	Ensure studies are adequately powered, based on appropriate *a priori* power calculations	Retrospective determination of post-hoc power where *a-priori* power calculations are not possible due to limited current data	*A-priori* power calculations (≥80% power) based upon previous data on the primary outcome variable for a given study (e.g. performance, GIS)	*A-priori* power calculations that ensure sufficient power (≥90%) for both primary outcomes and secondary mechanistic variables (e.g. gut microbiome/ metabolome)	Ensures that null findings are due to a lack of effect resulting from prebiotic supplementation, rather than insufficient participant sample size
Use of a homogenous group of participants	Participants should be similar in training status and age. Inclusion of highly trained, competitive athletes should be prioritized where possible, as they are often under-represented in sport science research	Participants fall within a pre-specified age bracket and meet a pre-specified training status/ fitness bracket (e.g. within a minimum and maximum $\dot{V}O_{2max}$ value) but may fall into a variety of sports/ categories	Participants adhere to fitness and age requirements, and all play the same category of sport (i.e. all play intermittent team sports, are all endurance athletes or are all strength/power athletes)	Participants should all fall within the same age/fitness/ sporting category, with considerations also given to factors such as sex, body composition and habitual dietary intake, with further grouping by these variables occurring if the sample size is sufficient	The gut microbiome and metabolome of highly trained athletes are likely to differ significantly from recreationally active individuals [25,26], and may differ between those from different sporting categories [28]. Responses to prebiotics may therefore differ if groups are not similar in baseline physiological and training characteristics [28]
Dietary standardization	Control of diet, in particular dietary fiber, as a minimum in the day (s) approaching measurements and on trial mornings. Researchers may also choose to prescribe 2–3 days low FODMAP diet prior to trials, to minimize GI discomfort during trials, as done previously [204]. However, this may not be ecologically valid, as research indicates that only ~15% of athletes adhere to a low FODMAP diet [205]	Participants complete a food diary in the 24—48-h period prior to their first trial and replicate this prior to subsequent trials	Participants complete a food diary over the 24–48-h period prior to trials, but the final breakfast and/or dinner prior to trials is standardized and provided by the research team, to maximize control and adherence.	Providing standardized meals for the entire 48-h period prior to trials and including some sort of measurement of nutritional intake, especially fiber, over the entire supplementation period (at least 1–2 days per week).	Macronutrient and micronutrient intake will influence fuel availability, inflammatory responses and potentially exercise performance [206]. Dietary fiber intake, in particular, will have a substantial influence on gut microbial diversity [207] and the abundance of gut metabolites, such as SCFAs [208]
Hydration	Baseline hydration status and intra-exercise fluid intake is measured and compared or	Baseline hydration status is quantified via urine or blood metrics, and trials do not commence unless	Participants consume ad-libitum fluid in their first trial, and this fluid volume is matched in subsequent trials	Participants are provided a personalized amount of fluid based off prior measurement of sweat losses during a	Exercise-induced hypohydration can increase markers of intestinal

Table 3. (*Continued*)

Study design/behavioral standardization recommendations

Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
	standardized across repeated exercise-based trials	participants meet pre-specified euhydration criteria		familiarization trial at identical exercise intensity, in a matched environment	epithelial injury, and the incidence of GIS [209]
Control of dietary intake during exercise	Shorter exercise protocols (<90 min) can likely omit CHO intake; however, omitting CHO intake in exercise > 90 min risks participants being unable to finish exercise protocols, or performance impairment	Participants consume ad-libitum fueling/CHO intake from a standardized source in their first trial, and this intake is matched in subsequent trials	A standardized amount of carbohydrate is provided across all trials (in $g \cdot h^{-1}$), and this is matched in subsequent trials.	Standardized carbohydrate intake during prolonged exercise is provided in $g \cdot kg\ BM^{-1} \cdot h^{-1}$ and is matched across trials, aligned with evidence that body size may impact exogenous carbohydrate oxidation [210]	CHO intake can impact markers of GI damage [211], meaning it must be standardized. CHO intake will also substantially impact performance, and is often a priority for athletes, so including adequate CHO maximizes performance during testing and improves ecological validity
Physical activity	Control of physical activity in the day(s) prior to trials	Refrain from strenuous physical activity for 24 h prior to trials.	Refrain from strenuous physical activity for 24-h prior to trials, plus replicate any activity performed 24–48 h prior to trials (verified via logs)	Extend the standardization of physical activity to the 72-h window prior to trials and verify this via actigraphy or smart watch data	Prior physical activity will significantly impact baseline physiological and perceptual responses, which may have consequent implications for exercise performance
Environmental conditions and thermal strain	Environmental conditions should be tightly controlled and matched across repeated exercise-based trials	Standardization of temperature and humidity across trials, together with measurement of temperature and humidity at regular intervals and statistical comparisons used to confirm no difference	Use of fans to simulate wind speeds that are ecologically valid for the exercise modality being performed	Standardization of wind speed, plus measurement of core temperature (rectal, gastrointestinal or esophageal) and potentially even skin temperature throughout trials	Hot environments may increase circulating markers that indicate reduced intestinal integrity [212,213], although conflicting evidence also exists [214,215]. Core temperature responses are also associated with the magnitude of intestinal epithelial injury [213], potentially obscuring the ability to isolate prebiotic effects if thermal strain differs between trials
Training load	Quantification of training load throughout the entire supplementation period(s)	Monthly exercise/ training logs	Weekly exercise/training logs	Daily training logs from athletes, practitioners or coaches, or objective data obtained from wearable devices (Actigraphy, GPS or Smart Watches)	Training load will be key drivers of physiological adaptations and therefore changes in exercise performance [216]. Significant changes in training load will also likely alter gut microbial diversity

(*Continued*)

Table 3. (*Continued*)

Study design/behavioral standardization recommendations

Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
					independent from the effect of prebiotics [37]
Timing of trials (all participants)	Ensure that trials occur at the same time of day to minimize the effects of diurnal physiological variation	Trials are conducted within at the same general portion of the day (e.g. morning or afternoon)	Trials starting at the same time of day (< ~20–30 min difference in starting time between trials)	Trials also occur on the same day of the week. However, standardizing day of the week may not be possible for female participants where standardization of menstrual cycle day/phase is required (see below)	Physiological responses to exercise [217], and many biomarkers, including sIgA and cortisol [218], show substantial diurnal variability. Standardization of day of the week is also potentially important due to proximity to the weekend, as weekend-weekday differences exist for some physiological markers [219–221]
Timing of trials (female participants)	For naturally menstruating females, ensure that trials occur during the same phase of the menstrual cycle. For oral contraceptive users, ensure that trials occur during the same pill-taking stage. Several review articles provide more detail on standardizing trials across the menstrual cycle [222–224]	Report menstrual characteristics and contraceptive use as well as menstrual cycle phase or pill-taking stage during testing	Conduct trials within the same menstrual cycle phase, confirmed via 2 months of calendar tracking data collected prior to study participation. For oral contraceptive users, ensure testing occurs during the same pill-taking stage	Conduct trials within the same menstrual cycle phase, confirmed via 3 months of calendar tracking data collected prior to study participation. Urinary ovulation testing and blood or salivary sex hormone concentrations used to verify menstrual cycle phase	Menstrual cycle phase [225] and hormonal contraceptive [226] use may influence GI function and exercise-induced GIS, potentially affecting responses to prebiotic supplementation

GIS, gastrointestinal symptoms; GI, gastrointestinal; $\dot{V}O_{2max}$, maximal oxygen uptake; FODMAP, fermentable oligosaccharides, disaccharides, monosaccharides, and polyols; SCFAs, short-chain fatty acids; CHO, carbohydrate; GPS, global positioning system; sIgA, salivary immunoglobulin A.

Table 4. Key measures and biomarkers that are relevant to prebiotic intervention studies in athletic cohorts, together with recommendations for minimum standard, strong practice and best practice when incorporating these measures into research.

	Suggested measures/biomarkers				
Domain	Recommendation	Minimum standard	Strong practice	Best practice	Explanation
Gastrointestinal symptoms	Measure GIS using validated scales during any exercise trials and ideally also at regular intervals throughout supplementation	Measure global GI discomfort periodically during exercise trials (e.g. using the Nieman et al. scale [227])	Capture specific GIS periodically during/after exercise trials, using the Gaskell et al. scale [120]	In addition to exercise-specific measures, capture weekly GIS throughout the entire study (e.g. via GSRS [228])	The use of validated questionnaires improves comparability between studies and improves the reliability of GIS assessments
Gut microbiome measures	Assess how the gut microbiome responds to prebiotics, with more detailed recommendations given previously [229]	Obtaining a single fecal sample prior to and after the prebiotic intervention, with microbial profiling using 16S rRNA gene sequencing	Obtaining stool samples at multiple timepoints during the intervention, with microbiome measures occurring using 16S rRNA gene sequencing	Microbiome measures at multiple timepoints using shotgun metagenomics	Stool samples represent a non-invasive method to assess how prebiotics alter overall gut microbial diversity and the abundance of specific species
Metabolomic measures	Measurement of SCFAs and other key metabolomic biomarkers, via stool and/or blood	Measurement of several specific fecal and/or plasma SCFAs (e.g. acetate, propionate, and butyrate) using targeted methods such as GC-FID or GC-MS	Repeated assessment of fecal and/or plasma SCFAs, plus additional markers such as bile acids and branched-chain fatty acids using targeted analyses such as GC-MS or LC-MS	Targeted assessment of both fecal and plasma metabolites, combined with untargeted approaches to characterize the wider metabolome, such as LC-HRMS or NMR	Provides insight into microbial metabolic activity, with stool reflecting luminal production and blood indicating systemic exposure, although both have limitations in fully capturing site-specific production and absorption
Intestinal barrier integrity measures	Either direct measurement of intestinal epithelial integrity and/or injury, or determination of the concentration of surrogate measures in blood	Measurement of surrogate markers of gastrointestinal damage and/or integrity in the blood, such as I-FABP, zonulin, LBP, claudins	Direct measurements of intestinal integrity, either via measurement of lactulose:mannitol or lactulose:rhamnose ratio	Direct measurements of intestinal integrity combined with indirect blood-based markers and possibly even the addition of emerging techniques that can specifically image the gut barrier [202]	Enables determination of whether the prebiotic intervention has improved gut barrier integrity and/or reduced intestinal epithelial injury, which is often disrupted during prolonged and/or strenuous exercise
Immune function	Determining immune function via the incidence of self-reported cold and flu symptoms, together with analysis of specific biomarkers, and potentially testing to confirm the presence of infections	Participants complete weekly/monthly questionnaires to determine the incidence of URS	Participants complete daily questionnaires to assess URS using validated questionnaires, such as the Jackson Questionnaire [230], or the Wisconsin Upper Respiratory Symptom Survey [231]	Suspected infections are confirmed using nasopharyngeal swabs analyzed by either multiplex PCR for a broad panel of respiratory pathogens, or targeted PCR assays for selected pathogens where resources are more limited. Key immune function markers such as sIgA are also measured during laboratory trials	Previous work indicates reduced duration of URS and increased sIgA secretion with prebiotic supplementation [110,111]. Training and match absence due to viral or bacterial infections will likely have adverse impacts on performance outcomes, so minimizing this is of high importance to athletes

GIS, gastrointestinal symptoms; GI, gastrointestinal; GSRS, gastrointestinal symptom rating scale; rRNA, ribosomal ribonucleic acid; SCFAs, short-chain fatty acids; GC-FID, gas chromatography with flame ionization detection; GC-MS, gas chromatography-mass spectrometry; LC-MS, liquid chromatography-mass spectrometry; LC-HRMS, liquid chromatography-high-resolution mass spectrometry; NMR, nuclear magnetic resonance; I-FABP, intestinal fatty acid binding protein; LBP, lipopolysaccharide-binding protein; URS, upper respiratory symptoms; PCR, polymerase chain reaction; sIgA, salivary immunoglobulin A.

appropriate, the inclusion of different doses of the same prebiotic may also help to elucidate the optimal dose for each prebiotic, together with whether this dose varies depending upon individual characteristics. Allowing adequate time after antibiotic use before enrolling on the trial is also important, along with controlling and recording the intake of emerging and candidate prebiotics, prebiotic foods and other supplements. This will help to ensure that any observed effects can be attributed specifically to the prebiotic being studied. An extensive list of considerations for researchers planning the supplementation component of a prebiotic study in an athletic population is provided in Table 2, including a tiering system ranging from minimum standard to best practice for each recommendation. Researchers designing trials with a limited budget should aim to at least achieve the minimum standard recommendations listed here, whereas projects with greater funding should aim for strong or best practice.

4.2 Study design and standardization considerations

Researchers designing prebiotic intervention studies in athletic populations should prioritize recruiting a sample size with adequate statistical power (≥80%) to detect a difference in the chosen primary outcome measure. Power calculations should be based on an effect size that is both statistically detectable and physiologically relevant, using data from previous studies where available. When reliable estimates of the expected between-group difference are unavailable, a moderate standardized effect size (Cohen's $d \approx 0.5$) may provide a pragmatic assumption for power calculations, although the magnitude of effect observed with prebiotics will likely vary substantially according to the prebiotic type, outcome measure and exercise context. Therefore, where possible, researchers should instead use outcome-specific estimates derived from previous studies when performing power calculations; for example, the expected differences in GIS scores, I-FABP concentrations or other pre-specific primary outcomes in comparable populations and exercise protocols. Researchers should also ensure that participants are relatively uniform with regards to training status and other sporting characteristics, to minimize within/between-group variability. Once a homogenous participant cohort has been established, the research team should ensure that they have sufficient controls and recording processes in place with regards to diet and physical activity/training load during the supplementation period and prior to trials. Other factors such as environmental conditions, measurement of thermal strain and fueling/hydration during testing protocols should also be carefully considered and standardized across repeated trials, ensuring the design chosen is appropriate for the exercise context being studied. These key study design variables and recommendations are listed and explained in detail below in Table 3.

4.3 Key variables and biomarkers

Alongside the key aspects of design related to sample size, supplementation, control variables, and exercise protocols, researchers must ensure there are clear and justified primary, secondary and tertiary outcome measures. In the context of biological samples and biomarkers, studies that focus primarily on gross-whole body outcomes, such as exercise performance, may take fewer samples and focus more on ensuring performance tasks are executed properly, with minimal external factors affecting effort levels. Research questions that are more mechanistic in focus (i.e. by what physiological pathways do prebiotics promote a specific outcome) may need to obtain a greater number of biological samples. Generally, researchers are encouraged to focus on outcomes and markers that have been altered by prebiotics in previous research, such as GIS, intestinal integrity/injury, URS, IgA secretion, gut microbial composition and SCFA concentrations. However, additional variables not covered in this section may be more appropriate to answer certain specific research questions. Therefore, the list of measures and biomarkers presented in Table 4 is not designed to be an exhaustive list of all potential variables that could be useful for prebiotic studies in athletes, nor are all variables needed to be measured for all studies. These markers do however present several key physiological measures that could be altered by prebiotic supplements, according to existing studies. Additional measures not included but mentioned earlier in the review (e.g. sleep, cognitive function, nutrient absorption) may also be useful to include in some studies, depending upon the primary research question(s).

5. Conclusions

As research on the gut–exercise axis continues to evolve, prebiotic supplementation has emerged as a promising tool for supporting GI health and modulating immune responses, with recent findings suggesting potential benefits for other areas such as exercise recovery, sleep, mood and cognitive function. The growing body of evidence suggests that targeting the gut microbiome through prebiotic intake can reduce exercise-associated GIS, strengthen the intestinal barrier and reduce URS, at least in certain sub-populations of athletes and in specific contexts (i.e. in the competitive season, immediately post-competition, or under exertional heat stress). As both mechanistic and applied research in this area continues to develop, prebiotics could become an important component of future sports nutrition strategies.

From this review, it is evident that many gaps in the scientific literature still exist regarding prebiotic supplementation in athletic contexts, and more research is needed testing different prebiotic types to determine their role in altering physiological responses and subsequent health and performance outcomes. Moving forward, researchers should prioritize adequately powered, placebo-controlled studies in highly trained athletes, including measures of exercise performance, and high-quality assessments of GIS, gut microbial profiles, metabolomics, intestinal barrier integrity and immune responses where relevant. Future studies in female athletes are also warranted, as much of the current evidence involves only male participants. Registered dietitians and sports nutrition practitioners may wish to recommend prebiotic supplementation in specific scenarios, but this should be done on a case-by-case basis, and only after making an evidence-informed decision on prebiotic type, dose, timing and individual tolerance. The considerations provided in this article may help practitioners who are weighing up the advantages and disadvantages of prebiotics, but in all cases, prebiotics should be batch-tested and only prescribed by practitioners who have received the necessary education and training in the area of sports nutrition.

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