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## Probiotics: A Promising Shield against PFAS-Induced Gut Toxicity

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### Abstract

PFAS are a huge family of enduring synthetic chemicals commonly present in industrial and consumer goods because of their hydrophobic and oleophobic characteristics. They have caused significant health concerns to the people around the world because of their environmental stability and bioaccumulation capacity, which has resulted in contamination of water, soil, wildlife and human beings. PFAS has been linked to several negative effects in the event of chronic exposure, such as liver damage, thyroid dysfunction, immunotoxicity, developmental abnormalities, and heightened risks of cancer. Recent studies show that probiotics are an exciting gut-based treatment to counteract PFAS toxicity. Certain strains of Lactobacillus and

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Bifidobacterium can lower the absorption of PFAS by binding to the gastrointestinal tract, repairing intestinal barrier function, altering bile acid metabolism, and possibly biotransforming it. The preclinical evidence indicates that probiotics may help to reduce the inflammation caused by PFAS and improve the toxin excretion, yet the evidence is mostly animal-based. Major gaps are present such as the absence of adequate human clinical testing, incorrect dosage, and variation in efficacy by strain. Although

probiotics are a natural and inexpensive adjunct method, their combination into PFAS mitigation strategies is still to be validated. To effectively control the exposure of PFAS and related health hazards, the use of a multidisciplinary method that incorporates scientific studies, regulatory intervention, and community education is necessary.

**Keywords:** PFAS (Per- and polyfluoroalkyl substances), Forever chemicals, Environmental persistence, Human health impacts, Bioaccumulation, Toxic legacy

### Introduction

Per- and polyfluoroalkyl substances (PFAS) are a broad family of over 12,000 artificial anthropogenic chemicals admired for their hydrophobic and oleophobic features, allowing them to be utilized in various consumer products and other industries. The substances that are studied are often found in food-contact packaging, firefighting foams, non-stick cookware, and waterproof clothing [1].

PFAS are commonly known as forever chemicals due to their strong environmental persistence and their tendency to accumulate in the human body without a chance of being metabolized. Empirical studies carried out on a global level proved the widespread occurrence of the PFAS in drinking water, soil matrices, wild fauna, and even human serum [2].

Scientific anxiety is growing over the possible health impacts of long-term exposure to PFAS. Epidemiological and toxicological studies have also associated long-term exposure to many negative effects, including:

- Thyroid malfunction
- Damage to the liver
- Immunotoxicity (reduced response to vaccines in particular)
- High levels of cholesterol levels
- Infants and child developmental delays

- Increased the risk of some oncological diagnosis, such as kidney and testicular cancer [3].

### **The Toxic Legacy of PFAS**

A family of man-made molecules known as PFAS is often called forever chemicals due to their tremendous stability in the laboratory in terms of heat resistance, resistance to photolytic degradation, and chemical resistance. Due to these characteristics, PFAS compounds remain in soil, water, air, and even the geographically remote area like the Arctic decades after the initial release. They are easily able to biomagnify along the food chains thus contaminating the food provision and consumer products and eventually human populations using contaminated drinking water and other exposure routes [4, 5]. The PFAS are preferentially concentrated in the blood, liver and kidneys and they have biological half-lives that are much longer than the majority of toxins. There in vivo exposure has been associated with endocrine disruption, deregulation of liver enzyme systems, suppression of their immune system, serum cholesterol elevation, reproductive problems, developmental defects and an enhanced prevalence of metabolic disorders like malignancy of the kidney and the testicle. Such health issues have led the governments of the world to develop mechanisms of reducing the manufacture and use of PFAS [6, 7].

### **Enter Probiotics: A Gut-Centric Approach**

Recent research explores probiotics as a gut-focused strategy to reduce PFAS toxicity and absorption. PFAS can disrupt gut microbiota, leading to dysbiosis and related metabolic or inflammatory issues. Probiotics may help restore microbial balance, potentially reducing PFAS impact. Certain *Lactobacillus* and *Bifidobacterium* strains show promise in binding environmental toxins, suggesting potential to limit PFAS absorption, though direct evidence is limited [8]. Animal studies, like those by Ding et al., show that probiotic supplementation can reduce liver and gut inflammation caused by PFAS exposure. While human data are scarce, ongoing pilot trials aim to test whether probiotic capsules or fermented foods can lower PFAS biomarkers in blood and urine, especially in at-risk populations. Further clinical validation is needed [9].

### **Mechanisms**

*Lactobacillus* and *Bifidobacterium* genus probiotic strains have shown promise against chronic exposure to the chemical absorption, toxicity and bioaccumulation. In spite of the fact that the research is in its infancy, existing evidence concludes on three major mechanisms that should be explored (Figure 1):

**Biotransformation:** Some probiotic bacteria have surface compositions like peptidoglycans, teichoic acids, exopolysaccharides that are able to physically bind amphiphilic molecules such as PFAS within the gastrointestinal system. Such binding could prevent the uptake of PFAS into the bloodstream in the same way as it has been demonstrated that probiotics sequester heavy metals or endocrine disruptors such as BPA [10, 11]. These bound toxins can be eliminated through excreta in the form of feces, and any excess, which is mostly systemically inert, can be eliminated by forming PFAS-probiotic complexes to minimize the exposure and bioavailability of these toxins.

**Competition over nutrients, cellular binding and biological receptors:** PFAS exposure has also been linked to the damage of the intestinal tight junction and a marked effect on the permeability of the gut as well as elevated systemic uptake. This can be countered by probiotic intervention that can strengthen the intestinal lining: increase mucus secretion, escalate tight-junction proteins like occludin and claudin and suppress surrounding inflammation. This is due to the ability to prevent translocation of PFAS across the intestinal barrier which is prevented when probiotics are used and intestinal integrity of the gut is restored, which leads to reduced systemic exposure. Research shows that a negative exposure association is noted at a higher elevation than 5 m above sea level, indicating that altitude could alter gut absorption of PFAS [10, 11].

**Metabolic Degradation or Biotransformation:** Although the degradation of PFAS can be efficient when anaerobic bacteria in the gut are strong in reduction, those bacteria often lack sufficient reoxygenating potential to degrade these substances. However, recent developments suggest that some strain prototypes show the reductive defluorination of structurally comparable fluorinated compounds in low-oxygen environments. Despite the limited evidence recorded in the field of total PFAS biodegradation mechanisms carried out by probiotics, the current studies on the genetic tailoring of probiotic strains and the ability to catabolise the precursors of PFAS are promising set of future trends in the field of PFAS biodegradation carried out by probiotics [12].

**Modulation of Bile Acid Pathways:** FAS are structurally similar to bile acids, and this basically extends their circulation in the body since they have an extended enterohepatic circulation. Probiotics can interfere with the enterohepatic circulation by regulating the activity of the bile salt hydrolase and metabolism of bile acids. This mechanism amplifies the faecal discharge of PFAS bile complexes, which also reduces systemic accumulation of PFAS.

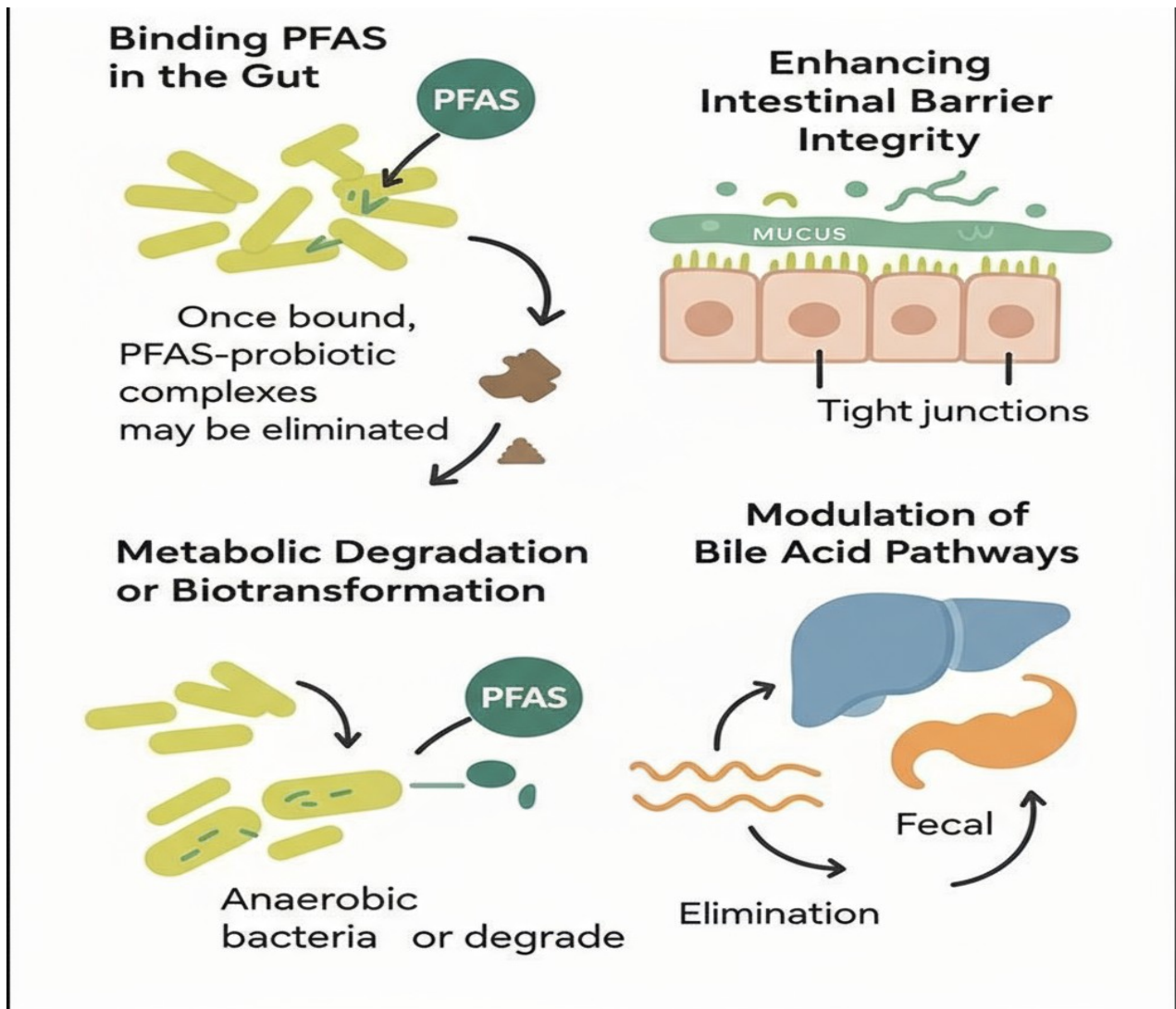
**Table 1: Mechanisms by Which Probiotics May Affect PFAS Burden**

Mechanism	Effect on PFAS	Probiotic Role
Binding in GI tract	Limits absorption into the	Cell wall adsorption

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	bloodstream	
Restoration of gut barrier	Reduces PFAS permeability	Tight junction restoration, anti-inflammatory effects
Potential microbial degradation	Possible breakdown of PFAS or precursors	Anaerobic fermentation pathways (under study)
Bile acid metabolism modulation	Alters PFAS enterohepatic recycling	Enzyme activity influences excretion



## Figure 1: Mechanisms by which probiotics may mitigate PFAS toxicity and promote elimination

### Scientific Evidence and Limitations

Scientific studies have provided early evidence that probiotics, particularly strains of *Lactobacillus* and *Bifidobacterium*, may mitigate the harmful effects of per- and polyfluoroalkyl substances (PFAS) by restoring gut microbial balance and enhancing fecal excretion of toxins. Animal studies have shown that probiotic supplementation can reduce PFAS-induced liver injury and inflammation, possibly through intestinal barrier repair and immune modulation rather than direct PFAS degradation. Some probiotics may also bind environmental toxins, suggesting a potential for PFAS binding [13]. Additionally, dietary fibers like pectin and inulin may help trap lipophilic compounds in the gut, aiding excretion. However, the evidence is mostly preclinical and lacks confirmation in human studies. The key limitations include the absence of large-scale clinical trials, undefined optimal dosage and treatment regimens, and the strain-specific nature of probiotic effects. The chemical stability of PFAS also limits probiotic action to gut-level reduction, with no ability to remove PFAS stored in internal organs [14]. Furthermore, real-world efficacy and safety data specific to PFAS detoxification remain scarce. Hence, while probiotics and dietary fibers offer promising low-cost interventions, their clinical application in PFAS mitigation requires extensive validation through rigorous human trials.

### Integrating Natural Solutions with Environmental and Policy Efforts

An expansion of literature on growing issues with the occurrence of per- and polyfluoroalkyl substances (PFAS) contamination is already available and points to the pressing need to adopt health-sustainable approaches. Acute data show that probiotics could be a potential, all-natural solution that can strengthen native detoxification routes either by binding or altering PFAS and dispatching to remove them through augmented gut microbiome capacity and sealed intestinal health. The results offer an easy translation, a biologically realistic process of PFAS removal that is compatible with larger suggested public-health guidance [15]. However, to prove these early findings, effective policy involvement would be required: governments must promote in-depth research into probiotics and must restrict the production of PFAS and promote PFAS-free alternatives and traditional water-treatment undermining technologies. In parallel with this, the education of the population is irreplaceable in providing knowledge and skills to the population in taking participatory actions in terms of dietary issues. Any probiotic measures incorporated into environmental policy and preventive care would have the potential to offer an overall, people-centered approach to addressing PFAS exposure management.

## Conclusion

Combat of the PFAS (per- and polyfluoroalkyl substances, or forever chemicals) requires the intersection of science, strong environmental policy, and health movements. The modern data show that probiotics can assist in the detoxification of PFAS and, thus, supplement regulations that are food-based. However, the current evidence is still inadequate in terms of explaining mechanisms, efficacy, or safety. There is a need to conduct studies to achieve optimal selection of the strain, its dosage, and long-term results. Tougher regulations, improved environmental surveillance and extensive community education should supplement nature interventions. Sustainable means of decreasing PFAS exposure and the encouragement of detoxification processes are dependent on the multidisciplinary paradigm, which combines scientific knowledge, policy framework, and popular consciousness.

## Conflict of Interest

The authors have no conflict of interest

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## Data Availability

All the data presented in this manuscript are original and have not been published elsewhere.

## Author's Contribution

TS: Study design and Concept

MMI: Reviewing and Editing

SS, MMJ: Writing the paper

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