



UNIVERSITY OF LIFE SCIENCES "KING MIHAI I" FROM TIMISOARA

"YOUNG PEOPLE AND MULTIDISCIPLINARY RESEARCH IN APPLIED LIFE SCIENCES"

13-14 November 2025



Probiotics and Inflammation: Insights into Gut-Immune Interactions

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Abstract: The intestinal microbiota is a central regulator of mucosal and systemic immunity, and its disruption is strongly associated with chronic inflammatory disease. Probiotics defined as live microorganisms that, when administered in adequate amounts, confer a health benefit on the host are increasingly used to modulate gut microbial communities and host immune responses. Experimental and clinical studies indicate that selected probiotic strains can reinforce barrier integrity, shape innate and adaptive immune cell function, and influence the production of immunoregulatory metabolites such as short-chain fatty acids. At the clinical level, probiotics show the most convincing benefit in specific settings, including induction and maintenance of remission in ulcerative colitis, prevention of antibiotic-associated diarrhea, and as adjuvant strategies in allergic and metabolic disease, although results remain heterogeneous across strains and indications. Here we synthesize current evidence on how probiotics influence gut-immune interactions, with a focus on mechanistic pathways linking microbial modulation to inflammation control and on the translational implications for immune-mediated diseases.

• Introduction

Inflammation that originates at the intestinal barrier can propagate beyond the gut through microbial translocation, systemic dissemination of microbially derived metabolites, and chronic activation of innate immune pathways. This concept helps to explain why intestinal dysbiosis is linked not only to inflammatory bowel disease, but also to extra-intestinal disorders such as metabolic syndrome, neuroinflammatory conditions and allergic multimorbidity. Understanding how commensal and probiotic microbes calibrate immune responses at the barrier surface therefore has broad relevance for immunopathology in distant organs. (3,5,14)

Probiotics are typically selected strains of *Lactobacillus*, *Bifidobacterium* and other genera with documented safety and putative health benefits. They are delivered as fermented foods or concentrated preparations and are increasingly combined with prebiotics and postbiotics in complex formulations. Despite widespread use, clinical results remain variable, reflecting heterogeneity in strain selection, dose, treatment duration and baseline microbiota composition. (1,2,6).

• Mechanisms of probiotic action on gut-immune interactions

Maintenance of barrier integrity: One of the best characterised actions of probiotics is the reinforcement of epithelial barrier function. In vitro and in vivo models show that selected strains increase the expression and correct localisation of tight junction proteins, stimulate mucin production and enhance epithelial restitution after injury. These effects limit paracellular permeability and reduce the translocation of luminal antigens and microbes into the lamina propria, thereby lowering chronic activation of innate immune sensors. (1,2,7)

Modulation of innate immunity: Many probiotic strains directly interact with dendritic cells, macrophages and epithelial cells via Toll-like receptors, NOD-like receptors and C-type lectins. Depending on the strain and context, these interactions skew antigen-presenting cells towards a tolerogenic phenotype characterised by increased IL-10 production, reduced expression of co-stimulatory molecules and altered chemokine profiles. In experimental models of colitis, this translates into reduced recruitment of neutrophils and monocytes and attenuated tissue damage. (2,7)

Microbial metabolites and immune regulation: The gut microbiota produces a wide repertoire of metabolites that act as signalling molecules for host cells, and probiotics can modulate both their quantity and quality. Short-chain fatty acids such as acetate, propionate and butyrate, generated from microbial fermentation of dietary fibre, engage G-protein-coupled receptors and inhibit histone deacetylases to promote regulatory T-cell differentiation, support epithelial energy metabolism and dampen inflammasome activity. Probiotic-driven shifts towards short-chain fatty acid-producing taxa therefore have profound implications for immune homeostasis. (5,14)

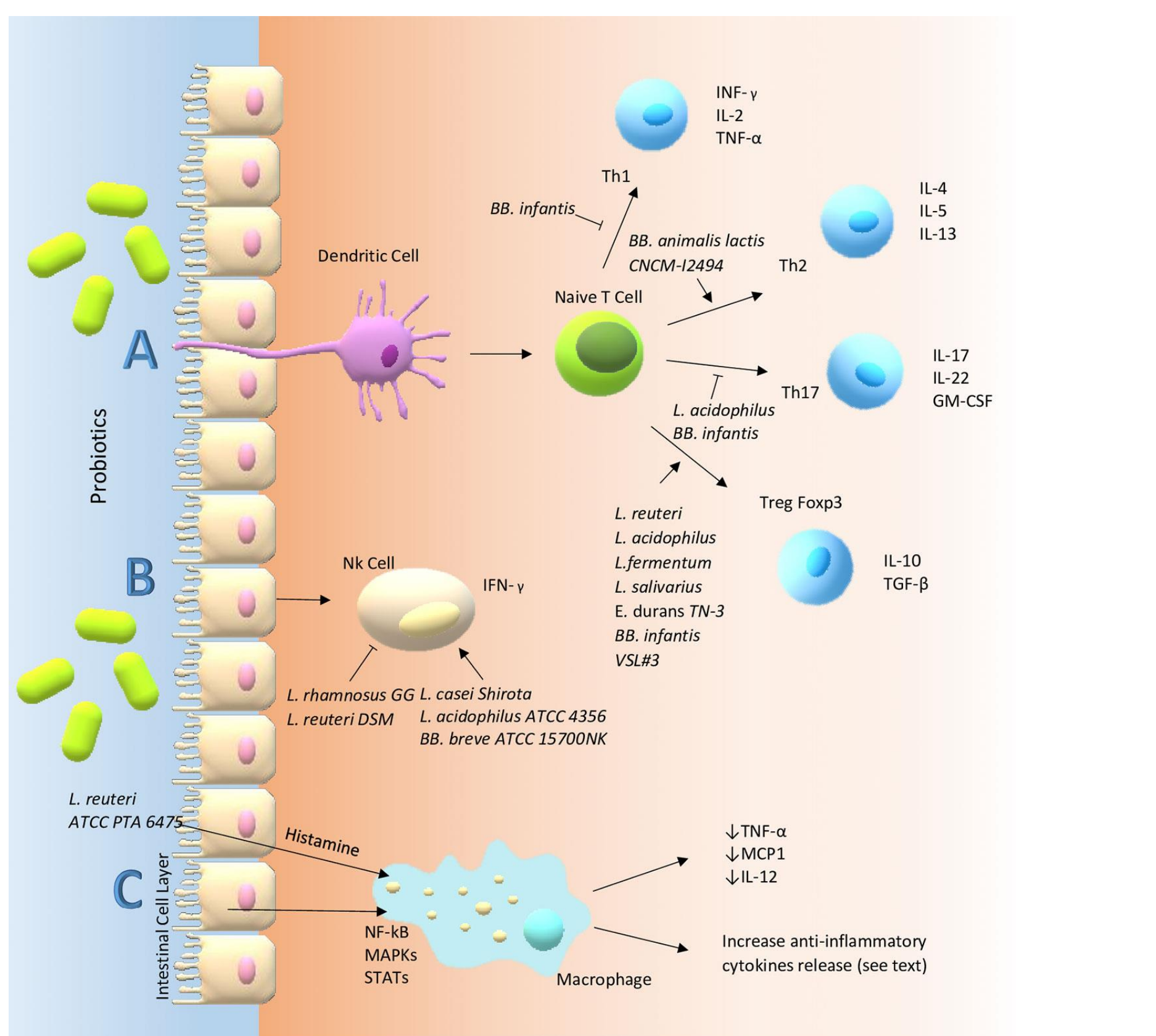


Fig. 1. Immunomodulation mechanisms of different probiotic types.

• Systemic consequences of probiotic immune modulation

Allergic disease: Recent meta-analyses indicate that probiotic supplementation can modestly reduce the risk or severity of several allergic outcomes, although effect sizes vary by timing, strain and clinical endpoint. In particular, antenatal and early postnatal administration of mixed-strain preparations appears to lower the incidence and severity of atopic dermatitis, while adjunctive probiotics may improve symptom control in allergic rhinitis and asthma when added to standard pharmacotherapy. These findings support the concept of probiotics as adjuvants that enhance tolerance-inducing pathways rather than as standalone antiallergic agents. (11,12)

Metabolic and cardiometabolic disorders: Systematic reviews of randomised trials suggest that probiotic supplementation can lead to modest improvements in body weight, waist circumference, blood pressure, lipid profiles and insulin sensitivity in individuals with metabolic syndrome or obesity, although results are inconsistent and strain dependent. Multi-strain formulations and longer intervention periods appear more likely to yield clinically relevant effects, possibly by more effectively remodelling microbial communities and reducing metabolic inflammation. These data support the inclusion of probiotics as adjunctive measures within comprehensive lifestyle and pharmacological strategies for cardiometabolic risk reduction. (10,15).

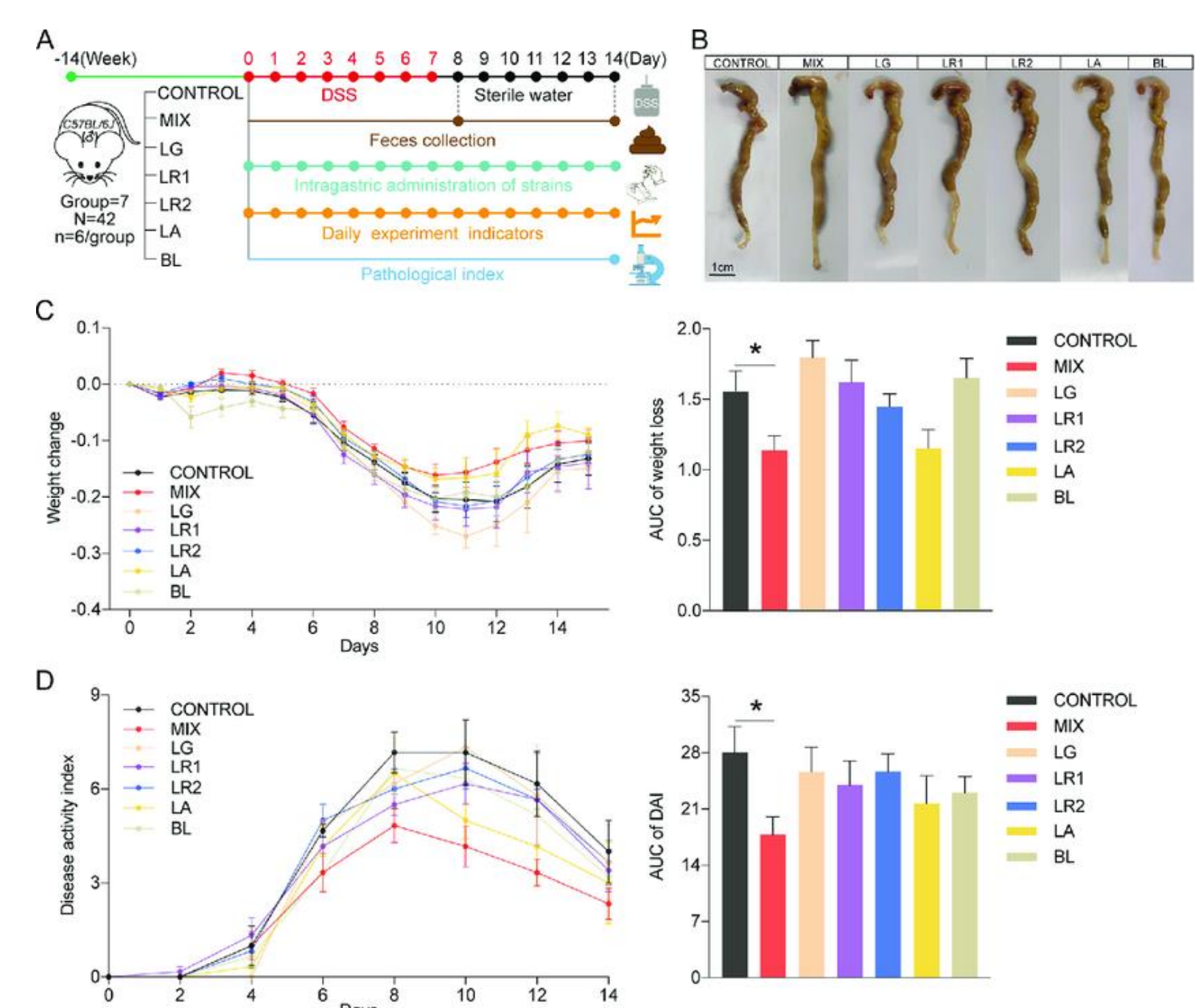


Fig. 2. (A) Schematic of the experimental timeline (CONTROL, control group; MIX, probiotic consortia; LR1, *Lactobacillus reuteri* PLBK1 group; LR2, *Lactobacillus reuteri* PLBK2 group; LG, *Lactobacillus gasseri* PLBK3 group; LA, *Lactobacillus acidophilus* PLBK4 group; BL, *Bifidobacterium lactis* PLBK5 group). (B) Representative images of colons for each group. (C) Weight loss and area under the curve (AUC) of weight loss for seven groups

Neuroinflammation and the microbiota-gut-brain axis: Human studies exploring probiotics as modulators of the microbiota-gut-brain axis report improvements in mood, cognitive performance and pain perception in subsets of patients with functional gastrointestinal and neuropsychiatric disorders, including fibromyalgia. Although effect sizes are generally modest and often confined to secondary endpoints, these findings suggest that targeting mucosal immune activation and microbial metabolism may offer new avenues for managing neuroinflammatory symptom clusters. Rigorous mechanistic trials with immune and neuroimaging readouts are now needed to substantiate these early signals. (6,13)

• Conclusions

The increasing resolution of microbiome sequencing and single-cell immune profiling opens the way towards precision microbiota modulation. Future probiotic strategies are likely to move beyond empiric supplementation towards rationally selected strain consortia tailored to individual microbial and immunological signatures. Integration of probiotics with dietary interventions that provide appropriate fermentable substrates may enhance colonization and functional impact, aligning with emerging concepts of personalised nutrition for immune health. (6,11,14)

Probiotics occupy a unique position at the intersection of microbiology, nutrition and immunology. By modulating gut microbial communities, reinforcing barrier integrity and reshaping innate and adaptive immune responses, they offer a biologically plausible means of attenuating inflammation in a range of mucosal and systemic disorders. Yet their clinical utility is currently constrained by heterogeneity in preparations and study designs, and by an incomplete understanding of strain-specific mechanisms. Realising the full potential of probiotics as tools to interrogate and therapeutically manipulate gut-immune interactions will require rigorously controlled, mechanistically rich studies that integrate microbiome, immune and clinical endpoints. (1-5)

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