



## Probiotics In Precision Health: Bridging Metabolic Regulation and Immune Function

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### ABSTRACT

Metabolic and immune-related disorders are characterizing a growing global health burden which are characterized by altered metabolic homeostasis, immune dysregulation, and chronic inflammation. Appearing confirmation, the important role of the gut microbiota is regulating the metabolism and immune function in host. Sometimes microbial balance(dysbiosis) has been disrupted which strongly associated with the development of metabolic disorders. The metabolic disorders are metabolic syndrome, type 2 diabetes mellitus, and obesity as well as immune-related conditions including allergies, autoimmune diseases, and inflammatory disorders. Probiotics, defined as live microorganisms that afford health benefits when present in adequate amounts, have gained considerable attention as potential therapeutic agents for restoring microbial equilibrium and improving host health. Probiotics apply beneficial effects through multiple mechanisms by modulating the composition of gut microbiota and devolping the integrity of intestinal barrier, regulation of immune responses, and production of bioactive metabolic compounds such as short-chain fatty acids. These mechanisms denote to reduced systemic inflammation, improved insulin sensitivity, lipid metabolism regulation, and immune tolerance which leads to influence both innate and adaptive immune responses. The immune responses are influenced by balancing pro- and anti-inflammatory cytokine production and promoting regulatory pathways in immune system. Eventhough clinical studies carry the role of probiotics as favourable additions in the prevention and management of metabolic and immune-related disorders. Continued research focusing on strain selection, dosage optimization, and personalized probiotic therapies is essential to enhance their clinical efficacy and translational potential.

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## 1. Introduction

In recent changes in life styles, diets and environmental factors, it is increasingly common to hear of the widespread nature of disorders affecting metabolic and the immune system (Cani & Delzenne, 2009; Turnbaugh et al., 2006). Worldwide, there is a growing incidence of several health conditions, including type two diabetes, inflammatory bowel disease, metabolic syndrome, obesity and autoimmune disorders (Larsen et al., 2010; Liu et al., 2018). These diseases place a significant strain on healthcare systems. These conditions often come about because of chronic inflammation and immune system malfunction as well as the disruption of natural metabolic processes (Belkaid & Hand, 2014; Sekirov et al., 2010).

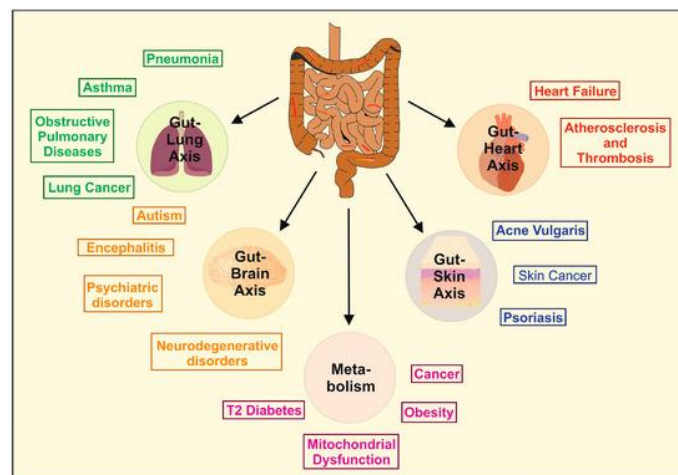
Imbalance of gut flora is linked to a variety of health problems including a weaker immune system and various metabolic problems (Round & Mazmanian, 2009). Strong evidence suggests that imbalance in gut flora, known as dysbiosis, has links to conditions including diabetes and various immune related diseases (Cani & Delzenne, 2009; Liu et al., 2018). Live beneficial microbes which offer health benefits when taken in sufficient amounts are known as probiotics (Hill et al., 2014). Such organisms are able to restore a healthy balance to the intestinal bacteria population and also promote the health of their host (Sanders et al., 2019).

Lactobacillus and Bifidobacterium species have the ability to influence nutrient metabolism, strengthen the gut barrier, and regulate the body's immune response (Bron et al., 2017; Plaza-Diaz et al., 2019). Research now shows that beneficial bacteria can improve the body's metabolic function by making the body more responsive to insulin, and by acting to reduce the levels of fat in the body and inflammation (Kobyliak et al., 2016; Mazloom et al., 2019). This process is governed by probiotics that modulate the immune system through influencing cytokine production and the body's inflammatory processes (Smits et al., 2005; Ng et al., 2018). They also play a part in the immune tolerance development (Arpaia et al., 2013).

With this combination of benefits, probiotics are now considered as a promising method for dealing with and preventing conditions linked to the immune system and metabolism (Ford et al., 2018; Koutnikova et al., 2019). The current position of the evidence regarding the use of probiotics in treating diseases of immune function and which influence metabolism is reviewed here, with specific attention paid to both their clinical benefit and to the mechanisms underlying their effects.

## 2. Gut Microbiota

Inside the human gut lives a busy world of tiny life forms called the gut microbiota (Sekirov et al., 2010; Thursby & Juge, 2017). Mostly made up of bacteria, it also includes archaea, viruses, and fungi that work together in subtle ways (Sekirov et al., 2010). Digesting food happens here, but so does making vitamins and shaping how immunity grows (Belkaid & Hand, 2014). When this inner balance gets disrupted – what scientists call dysbiosis – it often shows up alongside illnesses like diabetes, bowel inflammation, allergies, or even brain-related issues (Round & Mazmanian, 2009; Cryan & Dinan, 2012). Probiotics enter the picture not as magic fixes, yet still draw interest for their quiet influence on bringing stability back to these hidden communities (Sanders et al., 2019).



**Figure 1.** Applications of probiotics in the therapy of human diseases (Chandrasekaran, Weiskirchen & Weiskirchen, 2024). (Chandrasekaran et al., 2024).

### 2.1 Composition and Functions

Besides Firmicutes, Bacteroidetes make up most of the gut bacteria in people who are well (Sekirov et al., 2010; Thursby & Juge, 2017). After those, smaller groups like Actinobacteria show up, then Proteobacteria along with Verrucomicrobia (Sekirov et al., 2010). What lives inside the gut shifts depending on how old someone is, what they eat, their genes, daily habits, whether antibiotics were taken, or what surroundings they face (O'Toole & Jeffery, 2015). Fermenting fibers the body can't digest – this job belongs to microbes that keep the gut stable – and out come short-chain fatty acids: acetate, propionate, butyrate (Cani & Delzenne, 2009). Fuel for colon cells comes from SCFAs, while acidity levels in the gut get adjusted thanks to them, yet they also help calm inflammation (Arpaia et al., 2013). Immune balance starts with gut bugs that teach defenses when to back off instead of overreacting (Belkaid & Hand, 2014). Pathogens struggle to settle in because these helpful microbes

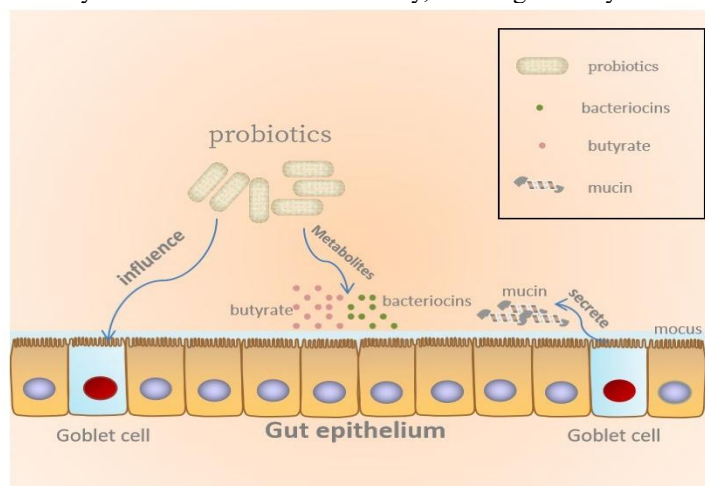
hog both food sources and space where invaders might latch on, which quietly lowers infection chances (Round & Mazmanian, 2009).

## 2.2 Probiotics: Definition and Characteristics

Living microbes that give health perks when taken in right doses are what we call probiotics (Hill et al., 2014). Found often in types like *Lactobacillus*, *Bifidobacterium*, *Saccharomyces*, *Enterococcus*, and *Streptococcus* (Sanders et al., 2019). These helpful bugs need to withstand stomach acid, bile, plus tough gut enzymes just to make it through (Bron et al., 2017). Sticking to the lining of the intestines is another thing they've got to do well (Bron et al., 2017). Something interesting happens when certain microbes settle in the gut – they shift which bacteria live there (Zmora et al., 2018). These helpful bugs can also strengthen the lining of the intestines, making it harder for harmful ones to pass through (Plaza-Diaz et al., 2019). Instead of just crowding others out, they make natural compounds that block unwanted microorganisms (Plaza-Diaz et al., 2019). Their influence reaches into how the body responds to threats, quietly guiding immune activity (Smits et al., 2005). Yet each type behaves differently – what one does, another might not (Ng et al., 2018). A specific strain defines what actually takes place inside (Ng et al., 2018).

## 2.3 Interaction Between Probiotics and Gut Microbiota

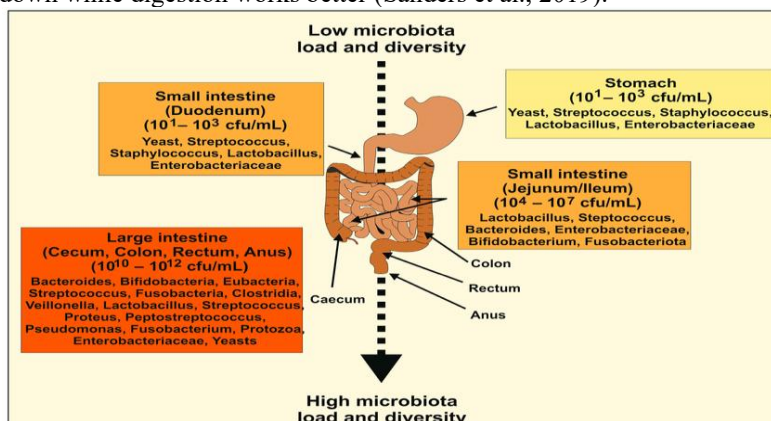
Now here's something odd – probiotics bump into the gut's native bugs in ways scientists still struggle to map fully (Zmora et al., 2018). For a short while, they set up shop inside your intestines, nudging the balance toward helpful microbes while quietly pushing harmful ones out (Kobyliak et al., 2016). It turns out these newcomers sometimes feed others just by leaving waste behind – a kind of underground dinner shared among friendly strains (Cani & Delzenne, 2009). One bug's trash becomes another's treasure, reshaping who survives down there (Cani & Delzenne, 2009). Besides their role in digestion, certain microbes strengthen the gut lining through increased activity of proteins that seal gaps between cells (Bron et al., 2017). These changes come alongside a rise in protective mucus layers, making it harder for unwanted substances to leak into surrounding tissues (Bron et al., 2017). Interaction with immune hubs in the intestine allows these beneficial strains to influence signaling molecules, shifting tendencies toward calming responses rather than aggressive ones (Ng et al., 2018). As a result, the body's internal balance shifts subtly, favoring stability over irritation (Ng et al., 2018).



**Figure 2.** Schematic representation of gut microbiota modulation by bioactive compounds (adapted from Nazzaro et al., 2021).

## 2.4 Health Benefits of Probiotics Through Gut Microbiota Modulation

**Gastrointestinal Health** – Most people take probiotics to help with gut issues like diarrhea from antibiotics or infections, along with IBS and inflamed bowels (Ford et al., 2018). When good bacteria return, swelling inside the gut tends to go down while digestion works better (Sanders et al., 2019).

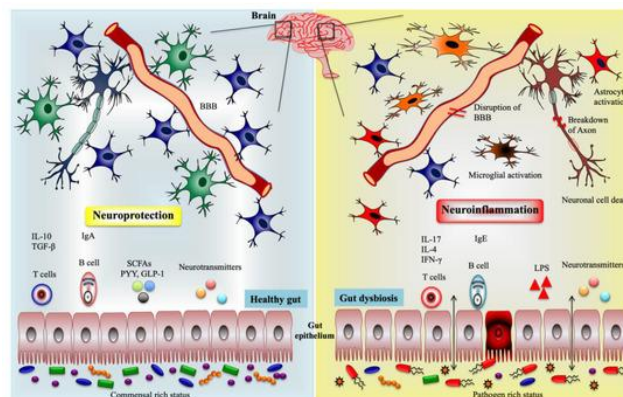


**Figure 3.** Microbiota load and diversity vary throughout the gastrointestinal tract (adapted from Effects of Probiotics on Gut Microbiota: An Overview, 2024).

**Metabolic and Immune Disorders** – Folks are starting to see how friendly bacteria might help control blood sugar, fat processing, and even waistlines (Mazloom et al., 2019; Koutnikova et al., 2019). Instead of just passing through, these microbes shift the balance in the gut, quietly dialing down ongoing internal irritation tied to stubborn health issues (Liu et al., 2018). Turns out, they also wake up both frontline and long-term defenses in the body's protection system (Ng et al., 2018).

## 2.5 Gut–Brain Axis

Signals travel from gut bacteria to the brain via a network known as the gut–brain pathway (Cryan & Dinan, 2012). Instead of just aiding digestion, these microbes can shape mood by making brain-active chemicals, calming hormone responses during pressure moments, while also quieting body-wide irritation (Cryan & Dinan, 2012). Research hints at benefits when using helpful bacteria to ease anxious thoughts, low moods, and conditions tied to ongoing tension (Cryan & Dinan, 2012).

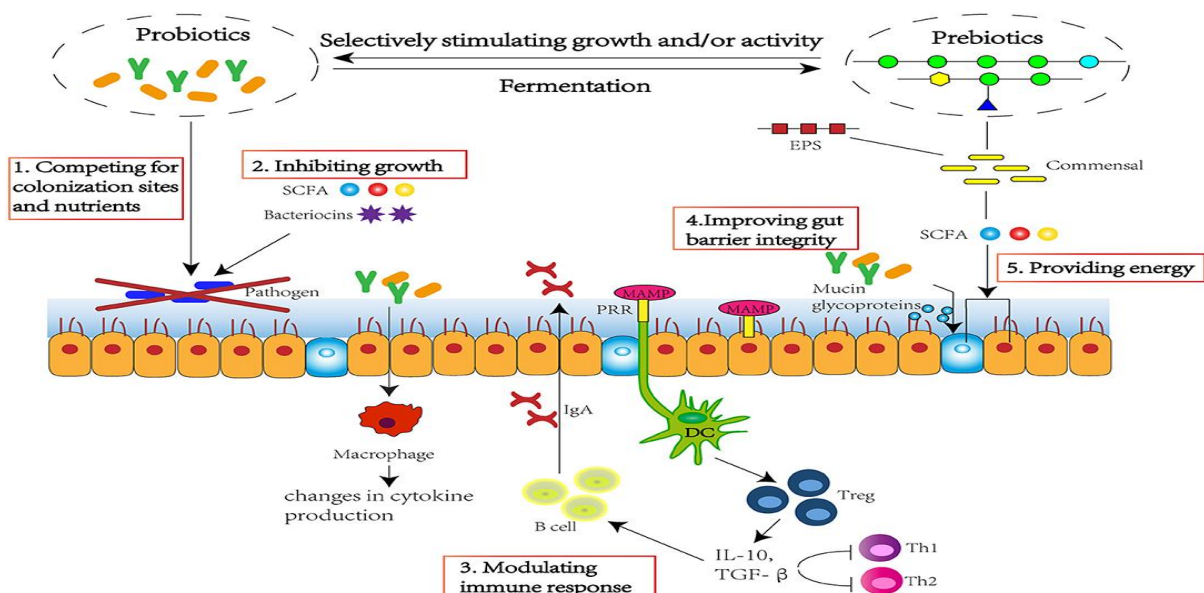


**Figure 4.** Influence of immune and metabolic regulation by the gut microbiota during the healthy and dysbiosis state via gut–brain axis (adapted from Suganya & Koo, 2020).

Probiotics may aid in the management of obesity because of their ability to control the energy harvested from food, decrease fat storage, and adjust appetite-related hormone levels (Kobyliak et al., 2016; Mazloom et al., 2019). Specific strains of probiotics, especially *Lactobacillus* and *Bifidobacterium*, have been documented to minimize the gain of body weight and adipose tissue in studies, both in humans and animals (Kobyliak et al., 2016; Koutnikova et al., 2019). These impacts are partially due to the creation of short-chain fatty acids (SCFAs), which promote feelings of fullness and boost lipid metabolism (Cani & Delzenne, 2009).

## 3. Gut Microbiota and Metabolic Regulation

Metabolic disorders, such as obesity, type 2 diabetes mellitus, dyslipidemia, and metabolic syndrome, are large-scale health issues (Cani & Delzenne, 2009; Turnbaugh et al., 2006). These disorders are characterized by impaired glucose metabolism, abnormal lipid profiles, chronic inflammation, and insulin resistance (Koutnikova et al., 2019). In recent years, the gut microbiota has been shown to play a role in the development and progression of metabolic disorders (Larsen et al., 2010; Cani & Delzenne, 2009). We note that in people with metabolic diseases, there is also a common change in gut microbial composition and function, which we term dysbiosis (Turnbaugh et al., 2006). Probiotics have emerged as an interesting dietary intervention to alter the gut microbiota and improve metabolic health (Kobyliak et al., 2016; Mazloom et al., 2019).



**Figure 5.** Metabolic pathways influenced by gut microbiota and probiotics (adapted from Ghanbari et al., 2021).

The gut microbiota plays a key role in host energy balance and metabolism (Cani & Delzenne, 2009; Sekirov et al., 2010). It plays a role in the breakdown of complex carbohydrates, production of short-chain fatty acids (SCFAs), bile acid metabolism, and regulation of inflammatory pathways (Cani & Delzenne, 2009; Thursby & Juge, 2017). In metabolically healthy individuals, the gut microbiota contributes to efficient energy use and maintenance of glucose and lipid homeostasis (Sekirov et al., 2010). However, in the case of dysbiosis, increased intestinal permeability, endotoxemia, and systemic inflammation are observed (Cani & Delzenne, 2009). Lipopolysaccharides (LPS) from gram-negative bacteria may enter the bloodstream and cause inflammatory responses, which in turn lead to insulin resistance and metabolic dysfunction (Cani & Delzenne, 2009). We also observed that the ratio of Firmicutes to Bacteroidetes plays a role in obesity and related metabolic issues (Turnbaugh et al., 2006).

### 3.1 Role of Probiotics in Metabolic Disorders

#### 3.1.1 Obesity

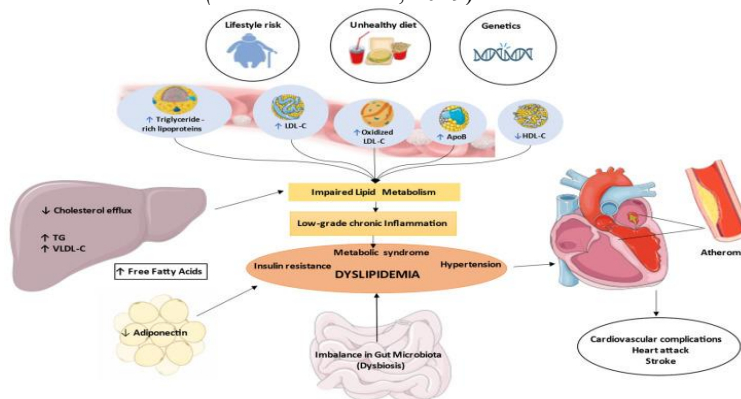
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#### 3.1.2 Type 2 Diabetes Mellitus

In type 2 diabetes, there is evidence of the positive impact of probiotics on glycemic control and insulin sensitivity (Ejtahed et al., 2012; Koutnikova et al., 2019). Probiotic supplementation has the potential to lower fasting blood glucose levels, glycated hemoglobin (HbA1c) levels, and certain inflammatory indicators (Ejtahed et al., 2012). Probiotics reduce overall inflammation, a major factor in insulin resistance, by strengthening the intestinal barrier and decreasing the translocation of endotoxins (Cani & Delzenne, 2009).

#### 3.1.3 Dyslipidemia and Cardiometabolic Risk

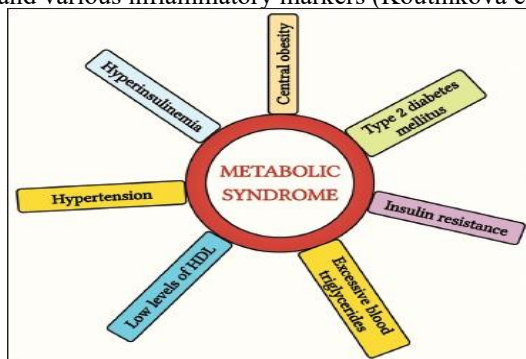
It has been suggested that probiotics may have a positive effect on lipid profiles by lowering total cholesterol, low-density lipoprotein (LDL) cholesterol, and triglycerides (Mazloom et al., 2019; Koutnikova et al., 2019). Proposed mechanisms include bile salt hydrolase activity, increased cholesterol elimination, and modification of liver lipid processing (Mazloom et al., 2019). Such effects lower the likelihood of developing heart problems associated with metabolic disorders (Koutnikova et al., 2019).



**Figure 6.** Nutrition and lifestyle interventions influencing cardiometabolic risk factors (adapted from Berisha et al., 2025).

#### 3.1.4 Metabolic Syndrome

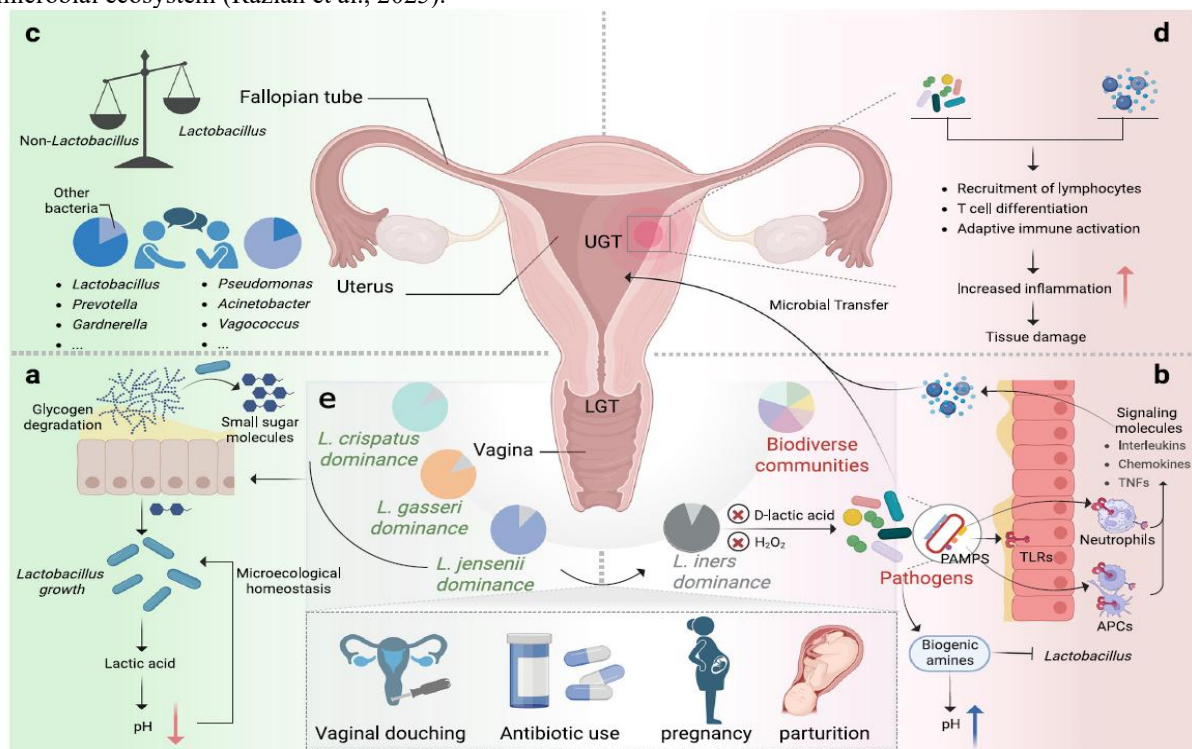
Metabolic syndrome is characterized by abdominal obesity, hyperglycemia, hypertension, and dyslipidemia (Koutnikova et al., 2019). Probiotics may improve various aspects of metabolic syndrome by decreasing inflammation, enhancing insulin sensitivity, and improving lipid metabolism (Mazloom et al., 2019; Kobyliak et al., 2016). Foods containing probiotics or probiotics in dietary supplements have shown benefits in waist circumference, blood glucose, and various inflammatory markers (Koutnikova et al., 2019).



**Figure 7.** Metabolic abnormalities in metabolic syndrome (adapted from Sinha & Narwaria, 2023).

### 3.1.5 Role of the Vaginal Microbiome in Health and Disease

In addition to maintaining reproductive health, the vaginal microbiome plays a vital role in preventing colonization by opportunistic and pathogenic microorganisms (Razian et al., 2025). A healthy vaginal environment is predominantly maintained by *Lactobacillus* species, which produce lactic acid, hydrogen peroxide, and bacteriocins that help sustain an acidic pH and inhibit pathogen growth (Razian et al., 2025). Disruption of this microbial balance results in vaginal dysbiosis, facilitating the overgrowth of anaerobic bacteria and fungal pathogens commonly associated with bacterial vaginosis, vulvovaginal candidiasis, and urinary tract infections (Razian et al., 2025). Factors such as antibiotic usage, hormonal fluctuations, hygiene practices, and sexual activity have been shown to significantly influence vaginal microbial composition (Razian et al., 2025). Consequently, conventional antimicrobial therapies, although effective in reducing pathogenic load, often fail to restore the natural microbiota, leading to recurrent infections and antimicrobial resistance (Razian et al., 2025). These challenges emphasize the importance of exploring alternative or complementary therapeutic strategies aimed at controlling pathogenic microorganisms while preserving or restoring the vaginal microbial ecosystem (Razian et al., 2025).



**Figure 8.** Microbial regulation of the female reproductive tract, showing *Lactobacillus* dominance, microbial transfer between the lower and upper genital tract, immune activation, and factors influencing vaginal microbiome composition (adapted from Cheng et al., 2025).

### 3.1.6 Mechanisms of Action of Probiotics

The positive effects of probiotics on metabolic disorders are complex and interrelated (Plaza-Diaz et al., 2019; Ng et al., 2018). Probiotics improve the composition of the gut microbiota by promoting the growth of beneficial bacteria and inhibiting the growth of harmful bacteria (Plaza-Diaz et al., 2019). They boost gut barrier function by upregulating the expression of tight junction proteins, which leads to less permeable intestines (Ng et al., 2018). They adjust the immune response by modulating the levels of certain cytokines and decreasing inflammation (Smits et al., 2005; Arpaia et al., 2013). Probiotics affect host metabolism by producing certain short-chain fatty acids (SCFAs), modifying bile acids, and impacting gene expression related to lipid and glucose metabolism (Cani & Delzenne, 2009; Plaza-Diaz et al., 2019). All these mechanisms improve metabolic homeostasis.

## 4. Probiotics in Immune-Related Disorders

Immune-related disorders developed during uncontrolled immune system, which may lead to conditions like inflammatory bowel diseases, autoimmune diseases, allergies and chronic inflammatory conditions (Belkaid & Hand, 2014; Round & Mazmanian, 2009). The immune system is linked to the gut microbiota, which plays a major role in immune system development, maturation, and regulation (Belkaid & Hand, 2014). Disturbance of gut microbial balance has been related with impaired immune responses and increased sensitivity to immune-mediated disorders (Round & Mazmanian, 2009). Probiotics have important attention as immunomodulatory agents which can able to restoring immune homeostasis (Ng et al., 2018; Plaza-Diaz et al., 2019).

### 4.1 Gut Microbiota and Immune System Interaction

The gut microbiota is a regulator of both innate and adaptive immunity responses (Belkaid & Hand, 2014). Mutualistic microorganisms give the development of immune tolerance and help in differentiation of harmful pathogens and harmless antigens (Round & Mazmanian, 2009). Dysbiosis can damage immune signaling which

leads to overstated inflammatory responses or immune suppression (Belkaid & Hand, 2014). Also Probiotics can maintain microbial balance and developing the immune stability by improving beneficial microbial populations and inhibiting pathogenic bacteria (Sanders et al., 2019).

#### 4.2 Immunomodulatory Mechanisms of Probiotics

Probiotics modulate immune function by some mechanisms, which includes activation of antigen-presenting cells, inflection of cytokine production and regulation of T-cell differentiation (Ng et al., 2018; Plaza-Diaz et al., 2019). They enhance anti-inflammatory cytokines like interleukin-10 while reducing pro-inflammatory mediators (Smits et al., 2005). Probiotics also strengthen intestinal barrier function, preventing the translocation of antigens that can activate immune responses (Ng et al., 2018).

#### 4.3 Role of Probiotics in Allergic Disorders

In allergic conditions, probiotics help to immune tolerance by maintaining the balance between T helper cell responses (Fiocchi et al., 2015). By helping regulatory T cells and reducing inflammatory signaling, probiotics can help alleviate allergic symptoms (Smits et al., 2005). Early-life of probiotic accessory has shown potential in reducing the risk and severity of allergic diseases (Kalliomäki et al., 2001; Fiocchi et al., 2015).

#### 4.4 Probiotics in Autoimmune Disorders

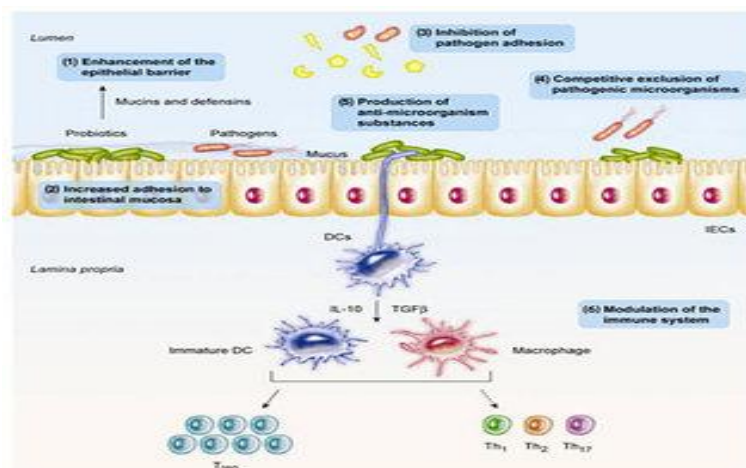
Some probiotic strains have been shown to suppress autoreactive immune responses and develop immune tolerance, suggesting their probable role as supportive therapy in autoimmune conditions (Tang et al., 2017; Liu et al., 2018).

### 5. Mechanisms of Action in Probiotics Immune-Related Disorders

Probiotics regulate immune functions by various, interconnected mechanisms involving the intestinal barrier, gut microbiota, intestinal barrier and host immune cells (Ng et al., 2018; Plaza-Diaz et al., 2019). These mechanisms come up with immune homeostasis and protection against immune-related disorders to enhancing the immune functions (Belkaid & Hand, 2014).

#### 5.1 Modulation of Innate Immune Responses

Probiotics play a crucial role in modifying innate immune system responses through interacting with intestinal epithelial cells, dendritic cells, neutrophils and macrophages cells (Ng et al., 2018). Probiotic-associated molecular patterns activate the controlled signaling pathways that enhancing the pathogen recognition while preventing large inflammatory responses (Plaza-Diaz et al., 2019). Additionally, probiotics are ability to produce the antimicrobial peptides, including defensins and cathelicidins, which is help to inhibit pathogen colonization (Ng et al., 2018). Interactions of immune response occurs primarily by pattern recognition receptors (PRRs). The PRRs are Toll-like receptors (TLRs) and NOD-like receptors which are expressed on epithelial and immune cells (Round & Mazmanian, 2009). They can also control phagocytic activity and enhancing the maturation of dendritic cells between the balanced immune phenotype (Ng et al., 2018). By fine-tuning innate immune activation, probiotics can strengthen the first line of host defense without inducing chronic inflammation (Plaza-Diaz et al., 2019).



**Figure 9.** Probiotic Mechanisms of Action (Source: Hill et al., 2014; Ng et al., 2018)

#### 5.2 Regulation of Adaptive Immune Responses

Probiotics influence acquired immunity through modulation of T-cells and making differentiation, promoting regulatory T cells (Smits et al., 2005; Ng et al., 2018). They can affect antigen presentation by dendritic cells, leading to controlled activation of T lymphocytes (Plaza-Diaz et al., 2019). Probiotic strains can improve the differentiation of regulatory T cells while maintaining a balanced ratio of T helper cell subsets like Th1, Th2, and Th17 cells (Smits et al., 2005). This regulation is important for preventing immune dysregulation associated with allergic reactions and autoimmune diseases (Fiocchi et al., 2015; Liu et al., 2018). Probiotics can also enhance IgA production in the gut-associated lymphoid tissue, which contributes to mucosal immunity and prevents pathogen adherence (Ng et al., 2018).

### 5.3 Cytokine Profile Modulation

Probiotics can improve anti-inflammatory cytokines during suppressing pro-inflammatory mediators which helping to control chronic inflammation (Plaza-Diaz et al., 2019). One of the most important immunomodulatory of probiotics are ability to alter cytokine profiles (Ng et al., 2018). Probiotics can also improve the production of anti-inflammatory cytokines by interleukin-10 (IL-10) and transforming growth factor- $\beta$  (TGF- $\beta$ ), which suppress large amount of immune activation (Smits et al., 2005; Arpaia et al., 2013). In the same time, they decreasing the secretion of pro-inflammatory cytokines which are tumor necrosis factor- $\alpha$  (TNF- $\alpha$ ), interleukin-6 (IL-6), and interleukin-17 (IL-17) (Ng et al., 2018).

### 5.4 Enhancement of Intestinal Barrier Function

Probiotics improves epithelial integrity by enhancing the strengthening tight junctions and mucin production (Ng et al., 2018). The intestinal epithelial barrier is important for preventing inappropriate immune activation (Belkaid & Hand, 2014). Probiotics strengthen this barrier by developing the expression of tight junction proteins like zonula occludens, occludin and claudins (Plaza-Diaz et al., 2019). They can also stimulate mucin production by goblet cells, forming a mucus layer that limits pathogen contacts with epithelial cells (Ng et al., 2018). Enhanced barrier integrity decrease intestinal absorbant, commonly referred as “leaky gut,” which means related with autoimmune and inflammatory diseases (Belkaid & Hand, 2014). By inhibiting the translocation of microbial antigens and toxins into the bloodstream, probiotics reduce immune overstimulations and systemic inflammation (Ng et al., 2018).

### 5.5 Induction of Immune Tolerance

Probiotics enable the tolerogenic dendritic cells and regulatory immune pathways (Smits et al., 2005; Arpaia et al., 2013). They improve the development of tolerogenic antigenic presenting cells which approval the generation of regulatory T cells rather than inflammatory effector T cells (Ng et al., 2018). This mechanism is important in preventing hypersensitivity reactions (Fiocchi et al., 2015). By continue submission to probiotic antigens, the immune system learns to differentiate the harmful pathogens and harmless antigens (Belkaid & Hand, 2014).

## 6. Clinical Evidence

Grid research has developed an association between probiotic therapy and gut health, confirming that probiotics have the potential to improve the human condition (Sanders et al., 2019). Probiotic clinical research has been conducted in the last 20 years consisting of randomised controlled trials, cohort studies and meta-analyses of clinical data showing how well these interventions work compared to each other and across a variety of clinical presentations (Ford et al., 2018; Hill et al., 2014). While all reports of efficacy point to an association of probiotics to the clinical improvement of disease states, the actual clinical outcomes depend on a number of factors such as strain of microorganism being used, dose and host responses (Hill et al., 2014). It is clear that probiotic therapy has a positive impact within the gastrointestinal tract (Sanders et al., 2019). Patients with GI disorders have seen clinical improvement with use of probiotics as documented by numerous clinical trials showing that probiotic use leads to decreased time and severity of antibiotic-associated and infectious diarrhea, particularly in children and the elderly (McFarland, 2015; Ford et al., 2018). *Lactobacillus rhamnosus* GG and *Saccharomyces boulardii* are widely studied probiotic strains which have demonstrated favourable outcomes in random controlled human studies (McFarland, 2015). The same is true in cases of IBS, where probiotics are known to relieve IBS symptoms such as abdominal pain, bloating and increased stool frequency, however, these outcomes vary by strain (Ford et al., 2018).

As the growing research base supports the use of probiotics as a treatment for metabolic syndrome, current human intervention trials suggest that individual probiotic strains have a significant impact on insulin resistance, reduction in chronic low-grade inflammation, and changes in the lipid profile in obese and type 2 diabetic patients (Koutnikova et al., 2019; Mazloom et al., 2019).

## 7. Future Perspectives: Role of Probiotics in Metabolic and Immune-Related Disorders

The rapid advances in microbiome science present probiotics a promising therapeutic agent for the avoidance and management of metabolic and immune-related diseases (Sanders et al., 2019; Hill et al., 2014). Although current evidence supports the therapeutic advantages of probiotics in conditions like obesity, type 2 diabetes mellitus, inflammatory bowel disease, and autoimmune disorders (Kobyliak et al., 2016; Ejtahed et al., 2012; Ford et al., 2018; Liu et al., 2018), future research is expected to change from empirical supplementation to precision-based probiotic therapeutics (Zmora et al., 2018; Cani et al., 2022).

### 7.1 Precision Probiotics and Personalized Medicine

One of the most significant future directions is the development of precision probiotics that are customized which are tailored to an individual's gut microbiota composition, genetic background, lifestyle choices, and immune condition (Zmora et al., 2018). High-throughput sequencing and metagenomic analysis have made it possible to fully define microbial dysbiosis associated with metabolic syndrome, insulin resistance, and chronic inflammation (Zmora et al., 2018; Koutnikova et al., 2019). Personalized probiotic formulations may optimize host-microbe interactions, increasing therapeutic efficiency and decreasing inter-individual response variability by precisely restoring beneficial taxa and metabolic pathways (Zmora et al., 2018; Cani et al., 2022).

## 7.2 Next-Generation Probiotics and Microbial Consortia

Traditional probiotics come primarily from *Lactobacillus* and *Bifidobacterium* species (Hill et al., 2014; Sanders et al., 2019). Future studies will focus more on next-generation probiotics, such as commensal anaerobes like *Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, and *Bacteroides* spp. that have strong immunomodulatory and metabolic maintaining properties (Cani et al., 2022). These organisms have been shown to affect immunological tolerance, the generation of short-chain fatty acids (SCFA), and the integrity of the gut barrier, making them attractive candidates for the treatment of metabolic inflammation and autoimmune diseases (Arpaia et al., 2013; Cani et al., 2022).

## 7.3 Probiotic-Derived Metabolites as Therapeutics

Applications may change in the future to include living microorganisms, postbiotics, and microbial metabolites such bile acid metabolites, indole derivatives, and SCFAs (Aguilar-Toalá et al., 2018; Plaza-Diaz et al., 2019). By controlling T-regulatory cells, suppressing pro-inflammatory cytokines, and altering glucose and lipid metabolism, these bioactive substances directly affect host metabolic and immunology signaling pathways (Arpaia et al., 2013; Ng et al., 2018). The safety and stability issues with live probiotics, especially in immunocompromised individuals, may be resolved by using certain microbial metabolites (Aguilar-Toalá et al., 2018; Sanders et al., 2019).

## 7.4 Integration with Immunotherapy and Metabolic Drugs

Probiotics can enhance immunological and metabolic drug responses by affecting immune tone and gut microbial composition, according to new research (Davar et al., 2021; Zmora et al., 2018). In the future, probiotics may be used as an adjuvant therapy to enhance treatment results when combined with immune checkpoint inhibitors, anti-inflammatory drugs, or antidiabetic drugs (Davar et al., 2021; Sanders et al., 2019). For clinical translation, it will be essential to comprehend how probiotics, medications, and the microbiome interact (Zmora et al., 2018; Cani et al., 2022).

## 7.5 Regulatory Safety and Clinical Validation Challenges

Probiotics have promising potential, but there are obstacles to their medicinal use, including strain-specific efficacy, dosage uniformity, long-term safety, and regulatory compliance (Hill et al., 2014; Sanders et al., 2019). To determine the causal relationships between probiotic treatments and health outcomes, future research must concentrate on large-scale, carefully planned randomized controlled trials and mechanistic studies (Ford et al., 2018; Koutnikova et al., 2019). Unified regulatory frameworks are also necessary to guarantee probiotic product quality control and medical claims (Hill et al., 2014; Sanders et al., 2019).

## 8. Conclusion

Researchers now believe that beneficial bacteria known as probiotics, can have a significant impact on the diseases caused by a poor balance of the bacteria in the body's digestive system. Research has increasingly pointed to the significance of the gut in controlling the body's metabolic equilibrium, in regulating the immune system and in controlling inflammatory reactions. Conditions such as chronic inflammatory disorders, type II diabetes, obesity, autoimmune diseases, allergies, and metabolic syndrome are all exacerbated by a condition known as dysbiosis. Probiotics have been shown to assist in the correction of an imbalance in bodily microorganisms which is known as the microbial equilibrium.

Probiotics have several effects on the body. This includes the regulation of the immune system. Additionally, they maintain the integrity of the gut and produce fatty acids. The bacteria in the gut also are regulated by probiotics. Research into the effects of these organisms has demonstrated that they can enhance the body's sensitivity to insulin, improve the metabolism of lipids, reduce the body's inflammatory response and promote a more tolerant immune system.

However, the results often depend on the species of organism and can be affected by the health of the host. A number of challenges persist, including issues of standardization, of selecting the correct strains, of optimising dosages and long-term safety concerns. Further research should be on the precision-based treatments using probiotics, next generation probiotics and compounds produced by probiotics, but these should be backed by clinical trials which are large scale and well thought out. The use of probiotics might work alongside conventional medicine and treatment programmes to offer patients further protection against disease. Metabolic and immune-related disorders are being addressed by the safe, promising and biologically valid probiotics.

## Conflict of Interest

The authors declare that there is no conflict of interest.

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