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Harnessing the Power of Postbiotics: A New Horizon in Pathogen Defense

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Abstract

The composition and balance of the intestinal microbiota are fundamental to maintaining physiological homeostasis and overall wellness. Pathogen-induced dysbiosis can disrupt this balance, impairing normal gut function, leading to gut dysbiosis and potentially affecting metabolic, immune, and cognitive functions and affecting overall health. Traditional interventions like prebiotics, probiotics, and postbiotics have been widely used to support a healthy gut microbiome, yet the presence of immunosuppressive organisms in probiotics may present certain risks. This has sparked interest in postbiotics, a safer, non-viable alternative. Postbiotics are metabolic byproductsderived from probiotics that can offer health benefits with minimized safety concerns. This review delves into the mechanisms of gut microbiome modulation, postbiotic classification and benefits, the application of postbiotics in functional foods, and providing future perspectives for advancing postbiotic research.

Keywords: Dysbiosis, postbiotics, gut microbiota, antimicrobial activity

1.0 Introduction

The human gut microbiota is a complex ecosystem made up of trillions of microorganisms, such as viruses, fungi, bacteria, and other microbes. This diverse microbiome has coevolved with humans, influencing and being influenced by our lifestyle, nutrition, and physiology [1]. Maintaining the homeostasis of the gut is essential to human health. According to recent scientific investigations, gut microbiota homeostasis is essential for immune system regulation, and human metabolic homeostasis maintenance [2]. However, numerous diseases may arise as a result of dysbiosis of the gut microbiota like type 2 diabetes, inflammatory bowel disease (IBD) [3]. The selection of appropriate treatment strategies and interventions to restore and maintain gut microbiota equilibrium is critical for achieving overall health and treating associated disorders [4]. The importance of postbiotics in the medical industry has increased in correlation with increasing evidence of the gut microbiota's critical role in human health and disease. This is because this supplement can both promote health and treat disease by modulating the gut microbiota [5].

2.0 From Pre- and Probiotics to Post-biotics: The Evolution of Gut Health Interventions

The human gut is a complex ecosystem that affects every aspect of health, from immune system performance to digestion and even mental well-being. As our understanding of gut health has grown over time, numerous interventions targeted at improving and preserving this essential system have also been developed. Prebiotics and probiotics are two of these interventions that have received a lot of attention; more recently, the idea of postbiotics has become apparent as a promising new area in gut health [6] The ability of probiotics, prebiotics, and postbiotics to promote health and treat disease through modulation of the gut microbiota has increased their significance in the medical field, along with increasing evidence of the pivotal role the gut microbiota plays in human health and diseases [7]

2.1 Prebiotics: The foundation of Gut Health

Prebiotics are indigestible food ingredients that specifically promote the development and function of probiotics, the good bacteria in the digestive system. These substances, which are mostly present in foods high in fibre, such as fruits, vegetables, and whole grains, provide probiotics which are the beneficial bacteria that live in the gut, with food source. Prebiotics aid in the maintenance of a balanced gut microbiota, which is necessary for healthy digestion, nutrient absorption, and immune system performance. This is accomplished by encouraging the growth of probiotics [4]. To categorise a substance as a prebiotic, the following standards are applied: It needs to: (i) be resistant towards the acidic pH of the stomach; (ii) be able to be easily fermented by intestinal microbiota; (iii) be incapable of being hydrolysed by mammalian enzymes; and (iv) be able to selectively promote the growth and/or activity of intestinal bacteria, all of which improve the health of the host [8]. Early in the 1990s, when scientists started to realize how crucial dietary fibers were for fostering gut health, the idea of prebiotics originated. Prebiotics function by nourishing the good bacteria already present in the gut and fostering an environment that encourages their growth and activity, in contrast to probiotics, which introduce live bacteria into the digestive tract [4].

2.2 Probiotics: Enhancing Gut Microbiota

In 1953, Werner Kollath came up with the term "probiotic" and described them as live organisms that have vital roles in enhancing a range of health outcomes. According to the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) defined probiotics as "live microbes that, when given in sufficient amounts, provide health benefits upon host organisms" [9]. Numerous bacteria from the genera Propionibacterium, Bacillus, Lactococcus, Enterococcus, and Streptococcus have been considered to be those for probiotic status [10]. Probiotics can be found in dietary supplements and fermented foods like kimchi, kefir, sauerkraut, and yoghurt. They function by invading the gut, where they produce antimicrobial compounds, compete with pathogenic bacteria, and adjust immune function [11]. They bio-transform mycotoxins in food, produce vitamin K, riboflavin, and folate, ferment undigested fibre in the colon, and detoxify xenobiotics and environmental pollutants [9]. Research has demonstrated that probiotics can aid in the relief of several digestive disorders, including constipation, diarrhoea, and irritable bowel syndrome (IBS) as well as prevents UTIs [11]. Probiotics are not a one-size-fits-all treatment, regardless of their possible advantages. Probiotic efficacy can vary based on strain, dosage, and individual factors like the natural composition of the gut microbiota [4]. Even though multiple meta-analyses have confirmed their clinical effectiveness in treating a variety of illnesses, like acute gastrointestinal infections however individual reports are increasingly casting doubt on the safety and efficacy of probiotics, particularly in high-risk patients. Therefore, this has led to research into more specialized and unique methods for supporting gut health [12].

2.3 Postbiotics: The Next Frontier

The most recent development in treatments for gut health is the use of postbiotics. Postbiotics which are defined as "metabolic byproducts of probiotics that exert benefits to the host" [13]. They are also referred to as metabolites, biogenic, or Cell-Free Supernatant (CFS) [14]. Postbiotics are more stable and can be added to a variety of products, such as foods, drinks, and supplements, in contrast to live probiotics, which can be susceptible to changes in temperature, pH, and other environmental conditions. Postbiotics are a desirable alternative for people who want to enhance gut health without having to deal with the difficulties of keeping live bacteria in their system because of their stability [15]. Accumulated evidence coming from studies conducted in vitro promotes the utilization of postbiotics to protect against infectious illnesses. Abdelhamid and colleagues made a notable attempt, demonstrating that six CFS could inhibit the development of two multi-resistant clinical E. coli isolates (WW1 and IC2) [16]. Furthermore, with the exception of the skim milk CFS, all six CFS made from Man-Rogosa-Sharpe (MRS) broth or skim milk were efficient at preventing the formation of biofilm of E. coli strains [17].

3.0 The Different components of postbiotics and its bioactivities

The several components of postbiotics illustrate the various ways in which they boost overall health below:

3.1 Short Chain Fatty acids

The bacterial species that make up the microbiota produce unique substances that affect the health of the host, such as the well-known short-chain fatty acids. These are created when the gut bacteria ferments undigested carbohydrates and breaks down dietary fibres. It has long been known that fatty acids and their derivatives have strong antibacterial qualities, which makes them a good substitute for conventional antibiotics [18]. The three primary short-chain fatty acids are butyrate, propionate, and acetate [19]. Cultured isolates show that different types of enteric bacteria primarily use carbohydrates to produce butyrate and propionate. Small amounts of propionate are metabolised in the liver's periphery [20]. It has been shown that SCFAs, particularly butyrate, have strong anti-inflammatory properties through their inhibition of pro-inflammatory cytokines and growth promotion of regulatory T cells (Tregs), which aid in the regulation of inflammation. This is particularly crucial for diseases like Crohn's disease and inflammatory bowel disease (IBD) since an imbalance in the gut microbiota can result in persistent inflammation [21]. Moreover, acetate another common SCFA, is a fermentation product produced by the majority of gut bacteria. It can also be produced from formate by hydrogenotrophic acetogenic bacteria such as Acetobacterium using the Wood-Ljungdahl pathway [22]. Recent studies have demonstrated the crucial role that gut microecology plays in atopic dermatitis (AD) and have related the severity of AD to low levels of short-chain fatty acids (SCFAs), specifically butyrate and propionate. The amount of microorganisms that produce SCFA has dramatically decreased in AD patients, and animal models exhibit comparable patterns. Research on newborns and mixed-age groups shows that people with AD had lower SCFA levels than their healthy peers [23]. Additionally, a study reported that the MIC values for pig-derived Campylobacter coli strains tested with butyric and propionic acids were 2048 µg/mL [24]. In contrast, the inhibitory values of propionic acid and butyric acid, in other studies involving Vibrio harveyi or Salmonella Typhimurium ATCC 14028, ranged from 500 to 100 µg/mL respectively [25], [26].

3.2 Antimicrobial Peptides

The ability of Antimicrobial Peptides (AMPs) generated by microorganisms to impede the synthesis of macromolecules and break down microbial membranes through pleiotropic processes makes them effective agents against a broad spectrum of pathogens. The two primary categories of these peptides are ribosomal and non-ribosomal [14]. Bacterial ribosomes produce ribosomal peptides, which have strong antibacterial properties mainly by rupturing microbial membranes. These peptides, which are produced by almost all bacteria, are directed against the cytoplasmic or cell membrane components of pathogens. Ribosomal peptides have antibacterial properties that include (i) the bacterial cell membrane becoming acidic (ii) creating physical breaches that allow cells to seep out (iii) producing hydrolases that cause harm to the cellular wall (iv) disturbing delicate interior microbial components [27]. Since ancient times, fermented foods have employed bacteriocins (antimicrobial peptides or proteins) produced by a variety of bacteria, such as Eubacteria and Archaebacteria, for their strong antibacterial qualities. These antimicrobial regulations were observed through formation of pores on the pathogenic cell membranes, inhibition of spore formation, and modifications to the structural and functional characteristics of bacterial peptides [28]. Similar to this, it has been demonstrated that the bacteriocins generated by Lactobacillus taiwanensis cause disruption of protein structures in Salmonella gallinarum and Escherichia coli, which resulted in membrane lysis and inhibition of bacterial growth [29]. In contrast, complex enzyme systems called non-ribosomal peptide synthetases (NRPS) or polyketide synthases (PKS) are responsible for the synthesis of non-ribosomal peptides (NRPs). NRPs are synthesized from discrete amino acid building blocks without the aid of ribosomal machinery, in contrast to ribosomal peptides. These peptides can have a wide range of structures and roles, such as immunological regulation, biofilm destruction, enzyme inhibition, and antibacterial action. NRPs have great promise for a wide range of uses, including the creation of novel antimicrobial agents, because of their flexibility [22]. Additionally, postbiotics of L. paracasei showed antifungal action against Candida auris, shielding infected individuals and enhancing immune responses [30].

Moreover, there are studies reporting that synergies of AMP with antibiotics show good synergy effects for example, P10, an AMP combined with ceftazidime/doripenem and Nisin an AMP combined with colistin inhibit XDR A. baumannii and colistin-resistant P. aeruginosa [31]. Similarly, CEP-136, an AMP combined with rifampicin can inhibit the growth of E. coli, P. aeruginosa [32]. However, a study stated that AMP shows better MIC values compared to antibiotics. Three derivatives of p-133 AMP, bip-P-113, dip-P-113, and nal-P-133, exhibit good efficacy against E. faecium, with a low MIC of 4 µg/mL in contrast to 64 µg/mL for vancomycin [33].

3.3 Organic acids

Organic acids are essential in suppressing food spoilage bacteria, especially when they act as postbiotics. These acids, which are produced by bacterial fermentation and have the capacity to lower pH levels, include lactic acid (including its L and D isomers), acetic acid, and citric acid. These acids inhibit the growth of pathogens and spoilage organisms by generating an acidic environment [34]. Lactic acid and acetic acid, for instance, have a strong ability to lower pH levels in vitro and in vivo, which effectively controls pathogenic bacteria like Salmonella and Escherichia coli [35]. Another study indicates that postbiotics can directly impede the growth of Candida, offering a substitute for antifungal therapies. The lactic acid generated by Lactobacillus keeps the vaginal environment acidic, which is particularly useful in preventing the proliferation of Candida albicans, the yeast that causes vaginal yeast infections [36]. Studies conducted on P1, S11, and M7 Lactobacillus plantarum strains have shown that these strains can inhibit the growth of pathogenic bacteria by secreting different kinds of organic acids. This shows that creating new, broad-spectrum antibacterial agents for use in the food industry through the combination of various organic acids may be a feasible approach [35].

3.4 Hydroxyl radicals

Strong antibacterial agent hydrogen peroxide (H_2O_2) may be transformed into hydroxyl radicals, which have powerful oxidative characteristics. Lactic acid bacteria, particularly those that lack catalase, frequently create it when cultivated aerobically. The concentration of H_2O_2 has a significant impact on its antibacterial properties, and this concentration can change depending on the kind of bacteria and ambient factors like pH and temperature [37]. Due to its potent oxidising abilities, H_2O_2 injures cytoplasmic protein structures of bacterial cells, hence causing antibacterial activity. In vitro tests against methicillin-resistant Staphylococcus aureus (MRSA) have shown the efficacy of this mechanism in probiotic bacteria, including Bifidobacterium longum, B. infantis, Lactobacillus acidophilus, and L. rhamnosus breve. According to the study, the growth of Staphylococcus aureus was significantly suppressed by the hydrogen peroxide these probiotics provided [12]. It is implied that postbiotic compounds, such as hydrogen peroxide, may be a useful substitute for conventional antibiotics in the fight against infections and the avoidance of food spoilage [14].

3.5 Vitamins

In addition to their antimicrobial properties, probiotic bacteria may produce large quantities of vitamins in the stomach and inside food matrices. Vitamin synthesis in food matrices, particularly dairy products, is far higher than that of probiotic bacteria in the colon, where their production is negligible. This enhanced synthesis of vitamins is essential in suppressing pathogenic microorganisms [38]. Lactic acid bacteria and Bifidobacterium sp. produce vitamin K and other essential vitamins, as well as B-group vitamins, including folate, riboflavin, cobalamin, pyridoxine, thymine, niacin, and nicotinic acid [39]. Recently, it was discovered that probiotics that have been demonstrated to synthesise vitamin B12, including Lactobacillus sanfranciscensis, Lactobacillus reuteri, Lactobacillus rossiae, and Lactobacillus fermentum, include genes encoding enzymes required for the synthesis of cobalamin (B12) [40]. Strong antibacterial effects are demonstrated by vitamins produced by degrading probiotic microbes in experimental conditions. Amongst them, vitamin C works especially well because it may make lipids in bacterial cell membranes more acidic. The increased acidity causes the cell walls and membranes of bacteria to lyse, which stops the bacterium from growing [14].

3.6 Reuterin

Lactobacillus reuteri can produce and accumulate significant reuterin levels via an enzymatic reaction catalysed by glycerol dehydratase under anaerobic conditions [41]. Reuterin, often referred to as 3-hydroxypropionaldehyde [3-HPA], is an intermediary that ensures the cell replenishes NAD+ during the conversion of glucose from glycerol to 1,3-propanediol[42]. This dynamic compound is associated with the probiotic properties of L. reuteri; however, its inhibitory mechanism against microorganisms remains incompletely elucidated. It was proposed that reuterin may hinder DNA synthesis by inhibiting ribonucleotide reductase and/or by inducing oxidative stress in microbial cells, resulting in cell death primarily due to the depletion of thiol groups in glutathione, proteins, and enzymes [43].

4.0 The Process of Postbiobics Production

To manufacture postbiotics in a controlled and effective way for research and usage in culinary, pharmaceutical, and nutraceutical applications, researchers have looked into production strategies [44]. Figure 1 below shows some of the process which can be carried out.

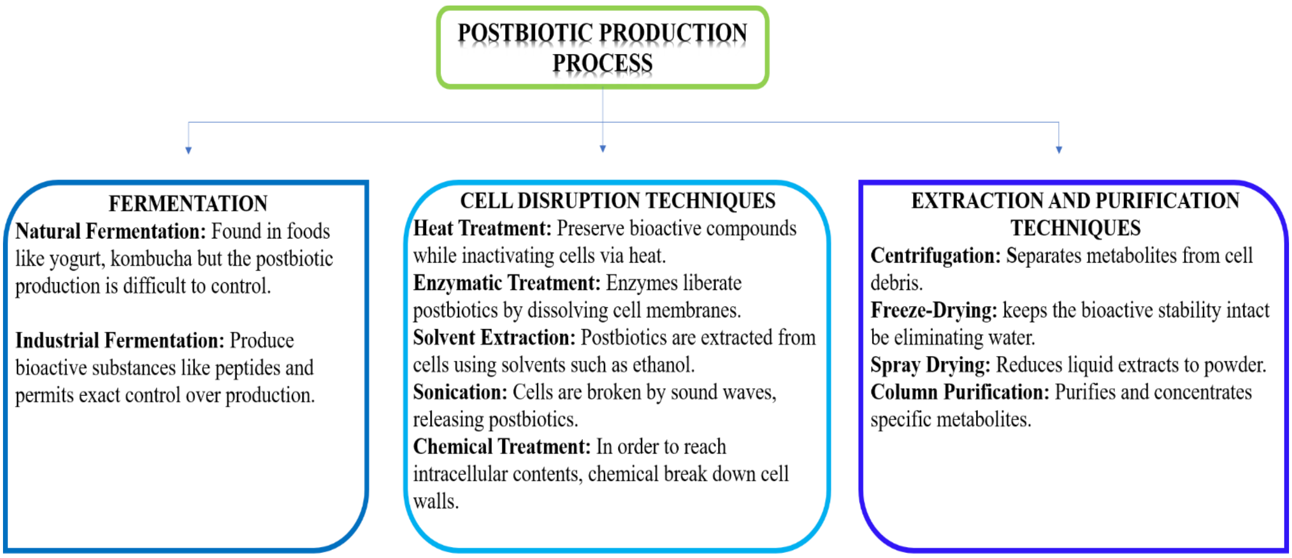

Figure 1 shows some of the different types of postbiotic production process.

The production of postbiotics were explained in some studies as mentioned below. Firstly, in order to create an antibacterial ground meat wrapping nanopaper, Shafipour Yordshahi et al. [45], created a lyophilized/freeze-dried powder with postbiotics from *Lactobacillus plantarum* ATCC 14917 that were integrated into bacterial nanocellulose. For local distribution in the small intestine, Puccetti et al. [46], created spray-dried microparticles containing postbiotics (indole-3-aldehyde) that are gastro-resistant. Nevertheless, the composition of extracted postbiotics may be altered by various processing methods, potentially resulting in a reduction in postbiotic activity. Additionally, in a study, postbiotic fraction of *Lactobacillus casei* ATCC 393 and examine its antiproliferative effects on cancer cells, the cells were heat-treated for 40 minutes at 100 °C, sonicated for 10 minutes at 50 W, and centrifuged for 40 minutes at 13,000× g [47]. In addition, in a study by Amaretti et al. [48], cell suspensions of strains of *Streptococcus, Lactobacillus, Bifidobacterium,* and *Lactobacillus* were ultrasonically disrupted five times at 0 °C for one minute each. The cell debris was then removed by centrifugation. The antioxidant capacity of the cell-free supernatants was assessed in vitro. By using sonication in a cooled water bath at 4 °C, followed by centrifugation and ultrafiltration. Also, Dunand et al. [49], discovered that the bio-functionality of cell-free postbiotics produced from milk fermented with *Lactobacilli* strains against *Salmonella* infection in a mouse model was effective.

5.0 The beneficial effects of Postbiotics

Postbiotics are a multifaceted complement which involves several bioactive substances with various modes of action. Most of the time, the effects which postbiotics contribute to human health and how they work are still unclear. Postbiotics are bioactive substances that probiotics make after they digest dietary fibers and other substrates. There are a number of possible ways that postbiotics might work [50] Some of the main ways that postbiotics may work are listed below,

5.1 Immune Modulation

Postbiotics have the ability to affect the synthesis of cytokines, which are immunological response-regulating signaling molecules. As an example, certain postbiotics have the ability to increase the production of anti-inflammatory cytokines and decrease the production of pro-inflammatory cytokines. This delicate balance can aid in the treatment of autoimmune diseases and persistent inflammation[51]. It was reported that HM0539, a postbiotic, inhibits pathogens while also modulating the immune system. In a DSS-induced mouse colitis model, HM0539 suppressed the expression of COX-2 and iNOS, reducing the generation of inflammatory mediators such as prostaglandin E2 (PGE2) and nitric oxide (NO). HM0539 reduced the TLR4-MyD88 and NF-κB signalling pathways, indicating its potential use in treating inflammatory bowel illness [52].

5.2 Antimicrobial activity

Postbiotics inhibit the development and colonisation of pathogenic bacteria in the gut by generating antimicrobial chemicals that cut down on their availability of space as well as resources [52]. Numerous postbiotics generate bacteriocins, which have antibacterial properties. For instance, the CFSM of several probiotics, such as *Bifidobacterium bifidum, Lactobacillus acidophilus, and Lactobacillus plantarum*, have shown potent antibacterial action against *Escherichia coli. L. plantarum* CFSM in particular showed the strongest antibacterial activity, preventing *E. coli* from forming biofilms by 64.57%. Bacteriocins usually cause intracellular components to move out, which results in the disruption of the bacterial cell membrane and eventual death of the cell [53]. *In vitro* tests on *Candida albicans* revealed the antifungal activity of postbiotics generated from probiotics such as *Lactobacillus rhamnosus* and *Lactobacillus casei*. Similar to this, cell-free supernatant (CFS) of *Lactobacillus kunkeei* showed suppressive properties against *Candida albicans*. These antifungal effects are probably caused by the bioactive substances that are created during the fermentation of probiotics. These compounds may change the integrity of the fungal membrane or impede the mechanisms that lead to fungal growth and biofilm development [54].

5.3 Modulation of Gut Microbiota

Postbiotics can foster an environment that is conducive to the development of good gut flora. Postbiotics reduce the pH of the gut by generating SCFAs and other metabolites, which encourages the growth of *Lactobacillus* and *Bifidobacteria*, two types of beneficial bacteria. By preventing the growth of harmful bacteria and fostering the equilibrium of microbial populations, postbiotics can also affect the whole composition of the gut microbiota [55]. Strong antibacterial action was demonstrated by CFS from *L. rhamnosus GG* against *E. coli* K1. In vitro, it prevented *E. coli* adhesion, invasion, and translocation by promoting mucin synthesis and shielding the intestinal barrier. In a model of newborn rats, CFS upregulated the production of mucin, MUC2, ZO-1, IgA, and Ki67, which decreased intestinal permeability and guarded against infection by *E. coli* K1 [56].

5.4 Metabolic Effects

It has been demonstrated that SCFAs, especially acetate and propionate, increase insulin sensitivity, which may aid in the management and prevention of metabolic diseases like type 2 diabetes. These SCFAs enhance the absorption and metabolism of glucose via acting on the liver and muscle tissues. By modifying the expression of genes involved in lipid production and breakdown, postbiotics can affect lipid metabolism and aid in the management of diseases including obesity and hyperlipidaemia [57]. It was reported that the CFS from *Lactobacillus plantarum* RG14 enhanced nutritional digestion and absorption in recently weaned lambs. It enhanced the number of fiber-degrading bacteria such as *Fibrobacter succinogenes* and *Ruminococcus flavefaciens*, which are essential for digesting down dietary fibre. Furthermore, the expression of IGF-1 (Insulin-like Growth Factor 1) and MCT-1 (Monocarboxylate Transporter 1) increased, indicating better nutrition transport along with metabolic processes in the gut [58]

5.5 Regulation of Gut-Axis

Certain postbiotics contribute to the synthesis of neurotransmitters, such as gamma-aminobutyric acid (GABA) and serotonin, which have an impact on mood, stress reactions, and mental health in general. Understanding the relationship between gut health and mental health requires a thorough understanding of this interplay between the stomach and the brain. Long-term usage of *Lactobacillus gasseri* CP2305 may enhance the gut microbiota, mental state, and quality of sleep-in healthy individuals under stressful situations, according to well-controlled clinical studies. Daily CP2305 substantially decreased anxiety, sleep disruption, and salivary chromogranin A levels when compared with the placebo in a 24-week randomized-controlled research that included students preparing for national medical tests ($p < 0.05$). Additionally, *Bifidobacterium spp*. reduction and *Streptococcus spp*. elevation generated by stress were mitigated by CP2305 [59]. It is reported that the Surface-associated ExoPolysaccharide (sEPC) of *Bifidobacterium longum* promotes gut barrier function by lowering inflammation and increasing tight junction integrity. These species stimulate the MAPK and Akt signalling pathways, which promote autophagy and calcium signalling, both of which are essential for tight junction integrity. *Bifidobacterium* species also create short-chain fatty acids (SCFAs), such as butyrate, that promote epithelial barrier function and metabolic health by regulating systemic energy balance and inflammation [60].

6.0 Common types of postbiotics and their antimicrobial activities

Postbiotics have promising antimicrobial characteristics without risks of live microorganisms. These compounds, which are derived from particular beneficial bacteria, have wide antimicrobial activities against infections and offer a safer method of maintaining gut health. The different types of postbiotics, their bacterial sources, origins, antimicrobial activity are categorised in table 1 below.

Type of postbiotic	Bacterial strain	Microbial supression	References
SCFAs	*Bifidobacterium*	*E. coli* O157:H7	[61]
Cell-Free Supernatant	*L. acidophilus* ATCC 4356	*Cl. perfringens, E. coli* and *S. aureus*	[62]
Bacteriocin	*Lactobacillus plantarum*	*L. ivanovii* BUG 496 and *C. tropicalis* R2 CIP203.	[63]
Vitamin B12	*Propionibacterium freudenreichii* DSM 20271	*Enterobacteriaceae* and *B. cereus*	[64]
Bacteriocin	*Lactobacillus casei*	Histamine-forming bacteria growth	[65]
Exopolysaccharides	*Lactobacillus gasseri*	*E. coli*, *L. monocytogenes* and *S aureus*	[66]
CFS	*Lactobacillus reuteri*	*S. agalactiae* and *A. hydrophila*	[67]
CFS	*Lactobacillus delbrueckii*	Human alphaherpesvirus HHV-1 and HHV-2	
Bacteriocin	*L. brevis DF01*	Biofilm formation of *E. coli* and *S.* Typhimurium	[68]

7.0 Challenges and Future perspectives

The scientific evidence covered in this review supports the effectiveness of postbiotics, due to their metabolic components, nonetheless more research are needed in addressing the key knowledge gap. In addition, more research are required to enhance delivery methods since oral administration may cause postbiotics to be metabolised before they reach their target sites, which would reduce their effectiveness. Moreover, the market for biotics is changing, and consumers are less aware of postbiotics and prebiotics than they are of probiotics. Although none are commercially available for use in food applications, postbiotics, as defined by ISAPP in 2021, have antibacterial, antioxidant, and antibiofilm properties, particularly from *Lactobacillus* [13]. Safety issues, a lack of clinical trials, and production difficulties are obstacles to their utilisation that could prevent their wider use in food technology [70]. Postbiotics, have health benefits that are comparable to those of probiotics and carry fewer hazards. If more research are done, postbiotics will be better understood on their composition, bioactivity, and modes of action [44]. Besides, more advances and cost-effective production techniques in postbiotic production techniques are needed. There should be more public awareness about the benefits of postbiotics to foster consumer demand and trust, which may thereby encourage larger-scale production [71].

8.0 Conclusion

The evidence offered throughout the review, not only deepens our knowledge about postbiotics but also shows how they have the potential to change the direction of pharmaceutical research. As the scientific community works to understand the complexities of the microbiome, the insights presented in this review solidify postbiotics as a crucial element in the pursuit of novel and sustainable solutions due to its balanced approaches that preserve the long-term well-being of human well-being. Lastly, this article's varied approach helps the growing corpus of research aimed at identifying the potential of postbiotics as a game-changing element in the fields of nutrition and health.

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