



REVIEW

Use of Postbiotic as Growth Promoter in Poultry Industry: A Review of Current Knowledge and Future Prospects

Muhammad Saeed^{1,†}, Zoya Afzal^{2,†}, Fatima Afzal³, Rifat Ullah Khan⁴,
Shaaban S. Elnesr⁵, Mahmoud Alagawany⁶, and Huayou Chen^{1,*}

¹School of Life Sciences, Jiangsu University, Zhenjiang 212013, China

²Department of Poultry Science, Faculty of Animal Production and Technology, The Cholistan University of Veterinary and Animal Sciences, Bahawalpur 63100, Pakistan

³Department of Life Sciences, Sogang University, Seoul 04107, Korea

⁴College of Veterinary Sciences, Faculty of Animal Husbandry and Veterinary Sciences, The University of Agriculture Peshawar, Peshawar 25120, Pakistan

⁵Department of Poultry Production, Faculty of Agriculture, Fayoum University, Fayoum 63514, Egypt

⁶Department of Poultry, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt

OPEN ACCESS

Received May 6, 2023

Revised August 23, 2023

Accepted September 7, 2023

*Corresponding author : Huayou Chen
School of Life Sciences, Jiangsu University,
Zhenjiang 212013, China
Tel: +86-13912800258
Fax: +86-0516-83403320
E-mail: hyc@ujs.edu.cn

*ORCID

Muhammad Saeed
<https://orcid.org/0000-0001-5048-5753>
Zoya Afzal
<https://orcid.org/0000-0003-0595-819X>
Fatima Afzal
<https://orcid.org/0000-0002-8726-8805>
Rifat Ullah Khan
<https://orcid.org/0000-0002-0924-0479>
Shaaban S. Elnesr
<https://orcid.org/0000-0002-4430-1492>
Mahmoud Alagawany
<https://orcid.org/0000-0002-8020-0971>
Huayou Chen
<https://orcid.org/0000-0002-1010-8205>

† These authors contributed equally to this work.

Abstract Health-promoting preparations of inanimate microorganisms or their components are postbiotics. Since probiotics are sensitive to heat and oxygen, postbiotics are stable during industrial processing and storage. Postbiotics boost poultry growth, feed efficiency, intestinal pathogen reduction, and health, making them acceptable drivers of sustainable poultry production. It contains many important biological properties, such as immunomodulatory, antioxidant, and anti-inflammatory responses. Postbiotics revealed promising antioxidant effects due to higher concentrations of uronic acid and due to some enzyme's production of antioxidants, e.g., superoxide dismutase, glutathione peroxidase, and nicotinamide adenine dinucleotide oxidases and peroxidases. Postbiotics improve intestinal villi, increase lactic acid production, and reduce *Enterobacteriaceae* and fecal pH, all of which lead to a better immune reaction and health of the gut, as well as better growth performance. P13K/AKT as a potential target pathway for postbiotics-improved intestinal barrier functions. Similarly, postbiotics reduce yolk and plasma cholesterol levels in layers and improve egg quality. It was revealed that favorable outcomes were obtained with various inclusion levels at 1 kg and 0.5 kg. According to several studies, postbiotic compounds significantly increased poultry performance. This review article presents the most recent research investigating the beneficial results of postbiotics in poultry.

Keywords postbiotic, antibiotic alternatives, mechanism of action, poultry

Introduction

One of the 20th century's greatest discoveries was the discovery of antibiotics, which made it possible to treat various diseases more easily. Antibiotics have several uses beyond the prevention and treatment of disease, including improving the health and well-being of animals used for human consumption (Durso and Cook, 2014). However, with the excessive use of antibiotics, other threats emerged that included antibiotic resistance in human and animal feed (Ma et al., 2021). Consumers should be aware that meat and meat products may contain residues that could be harmful to their health and even more dangerous to humans, as it is not physiologically apathetic even at low concentrations and over extended periods of time (Zamojska et al., 2021). According to the literature, postbiotics are “non-viable bacterial products or metabolic products obtained from microorganisms with biological activity in the host” or “the crude cell extracts that benefit the human or animal consumer when administered orally or topically in sufficient amounts” (Homayouni Rad et al., 2021; Patel and Denning, 2013; Thanh et al., 2009; Zendeboodi et al., 2020). Postbiotics are considered better than probiotics because postbiotics contain microorganisms that are incapable of replicating; they are less likely to cause bacteremia or fungemia than probiotics (Yelin et al., 2019). Furthermore, postbiotics offer several intriguing characteristics, such as different molecular structures, long shelf lives, and safety doses (Shigwedha, 2014). Postbiotics have good metabolism, absorption, distribution, and excretion, which could affect many host organs and tissues and perform many biological tasks (Shenderov, 2013). Therefore, promising antibiotic alternatives are required. The search for other options for improving growth and health practices has become the leading research endeavor. Poultry producers face the challenge of feeding the world while adhering to the regulatory mandates of their local jurisdictions. Bird growth and health can be enhanced with dietary manipulation of feed additives such as prebiotics, postbiotics, probiotics and herbal products (Arain et al., 2018; Arain et al., 2022a; Klemashevich et al., 2014; Nabi et al., 2020a). In animal production, probiotics are referred to as direct-fed microbials because they reside in the gut of animals and preferably serve a useful purpose. Prebiotics are composed of constituents the body cannot digest and are specially designed to promote the development of good bacteria in the gut. Finally, postbiotics are generally produced by beneficial bacteria of the gut products that must be fed and apply a beneficial effect on the host's health. Compared to the host, the intestinal microbiota contains more biochemical reactions and genomes, which significantly affect the host's development, health, metabolism, behavior, and immunity. At the same time, the disease caused by microbial imbalance is known as dysbiosis (Yeoman et al., 2012). Metabolizing host-indigestible feed ingredients is a crucial function of the gut microbiota. Consequently, the host can utilize feed more efficiently because of the microbiome's energy utilization ability. Additionally, the microbiota and metabolites they produce influence signal transduction in the host and regulate their response (Blacher et al., 2017; Loh et al., 2014).

Since most products have a long shelf life, postbiotics will remain stable during storage and production, but probiotics will die off. Probiotic strains die at different rates depending on their physiological traits and storage conditions (oxygen levels, temperature, water activity, duration, etc.). Thus, probiotic product dead cell counts in the last portion of their shelf life are difficult to generalize (Huber et al., 2005). Postbiotics are considered better than probiotics because postbiotics contain microorganisms that are incapable of replicating; they are less likely to cause bacteremia or fungemia than probiotics (albeit extremely rare; Yelin et al., 2019). Today, commercial poultry is regarded as the most available animal protein source (Arain et al., 2022b; Zuidhof et al., 2014). As the world's population grows and people shift to diets richer in animal protein, food animals must be produced safely and efficiently to feed this growing population (Nabi et al., 2020b; Wu et al., 2014).

In contrast to challenged non-treated chickens, Abd El-Ghany et al. (2022) reported postbiotic treatment improved disease

picture, growth performance, immune system stimulation, bursa/body weight ratio, and intestinal coliform counts compared to challenged non-treated chickens. Postbiotic compounds—dry or aqueous—improve broiler chicken performance, health, and immunity against colisepticaemia. Chang et al. (2022) found that *L. plantarum* postbiotic could replace antibiotic growth promoters (AGP) by improving gut health, beneficial bacteria colonization, mucin production, tight junction permeability, and immunity. Taken together, despite published literature on postbiotics being uncertain and lacking some imperative practical factors, new research has emerged regarding the possible health benefits of inactivated microbe.

Concepts of Postbiotics

The word “postbiotic” originates from Greek for the word “post”, relating to “after”, and “bios”, relating to “life”. There are many ‘biotic’ families that revolve around microbes (or their substrates), including prebiotics, probiotics, synbiotics, and postbiotics (Vinderola et al., 2022). Live microbes called probiotics are beneficial to the health of the host if administered at the proper level (Hill et al., 2014). The term postbiotic refers to cell fragments, non-viable or intact microbes, which may or may not contain metabolites and offer promising health benefits to the body (Vinderola et al., 2022). Through the metabolic process of bacteria and probiotics, soluble non-viable metabolites are considered postbiotics (Klemashevich et al., 2014; Tsilingiri et al., 2012). Postbiotics share a similar mechanism of action with probiotics, but as they are non-living organisms, they are different (Thanh et al., 2009). At the same time, purified metabolites are not considered postbiotics. International Scientific Association of Probiotics and Prebiotics (ISAPP) presented the postbiotic’s definition in mid-2021, stating that a postbiotic is “inanimate microorganisms or their component’s preparation which exert health benefits on the host.” ISAPP panel also considered other definitions focusing on microbes produced metabolites or other factors before deciding the final purpose of postbiotic (Salminen et al., 2021). In the different meanings of postbiotics, some stipulations also proved problematic. In addition, for live microbes, well-known health benefits do not necessarily expect that the advantage in an inactivated form will also be achieved. It would also hinder innovation from using such a definition since a probiotic should be established first, or the starting microbe should be limited to those already found as probiotics before meeting the criteria for a postbiotic when it is sufficient. There was some confusion regarding whether postbiotics were given to the target host or were formed *in situ* by resident microorganisms or administered microorganisms. The path to transformation into food, feed, and other final products is unclear if definitions do not distinguish between distributed and *in-situ* products. It turned out that different purposes required postbiotics to be applied to the gut lumen only (Tsilingiri and Rescigno, 2013), thus eliminating the opportunity of applying postbiotics to other surfaces. Efficient postbiotics include various *Lactobacilli* species present in cytoplasmic extracts and cell wall components that include *Lactobacillus casei*, *Lactobacillus acidophilus*, *Lactobacillus fermentum*, *Lactobacillus rhamnosus*, *Lactobacillus paracasei*, *Lactobacillus delbrueckii* subsp. *Bulgaricus*, *Lactobacillus gasseri*, *Lactobacillus helveticus*, *Lactobacillus reuteri* and *Lactobacillus Johnsonii* (Choi et al., 2006; Cicienia et al., 2016; Johnson et al., 2019; Kim et al., 2011; Matsuguchi et al., 2003; Tiptiri-Kourpeti et al., 2016; Vidal et al., 2002). The postbiotic phase includes soluble factors (products or metabolic byproducts), which are produced either as bacterial secretions or released after lysis, e.g., enzymes, peptidoglycan-derived muropeptides, teichoic acids, peptides, polysaccharides, cell surface proteins, and organic acids (Aguilar-Toalá et al., 2018).

Interaction of Postbiotics with Their Hosts

Various populations and even individuals have different gut microbiota compositions. A person’s metabolic and functional

phenotype is affected by the composition of microbiota present in the gut. It may result in individual differences in health effects from these biotics (Collado et al., 2009). Different '-biotics' or different individuals may exert diverse effects on the gut microbiota, as well as can also affect the composition over time. Consequently, adding probiotics, prebiotics, or synbiotics and many proposed health effects depend on the production of short-chain fatty acids (SCFAs) and other substances such as extracellular polysaccharides, functional proteins, microbial fractions, cell lysates, secreted polysaccharides, teichoic acid, pili type structures and muropeptides derived from peptidoglycans (Konstantinov et al., 2013; Markowiak and Śliżewska, 2017; O'Grady et al., 2019; Sánchez et al., 2017; Slavin, 2013; Wegh et al., 2017). Fermented matrix produces microbial metabolites, e.g., carbohydrates, proteins, lipids, vitamins, components of the cell wall, organic acids, or other complex structures, which affect postbiotic efficacy (Aguilar-Toalá et al., 2018; Konstantinov et al., 2013). The postbiotic composition may also be affected by food processing methods such as high pressure, irradiation, heat, and sonication (de Almada et al., 2016). So, postbiotic product composition and their host response are determined by the complete food production process (Taverniti and Guglielmetti, 2011). Postbiotic effects appear mediated by interactions between microbial products and the host. Thus, the host immune system can be activated, triggering, e.g., anti-inflammatory responses (Gosálbez and Ramón, 2015). Also, postbiotic compounds from *Lactobacilli* spp. may apply immunomodulatory action by reducing Th2-associated cytokines and increasing Th1-related cytokine levels (de Almada et al., 2016). The pili are structures of cell surfaces known to be part of the cause of the contact between the immune system and bacteria. Pili loss, for example, has been associated with reduced cell proliferation stimulation and better production of pro-inflammatory markers like IL-8 as well as a reduced ability of Caco-2 cells to resist radiologically induced bowel injury (Lebeer et al., 2012). Extracellular vesicles and exopolysaccharides (EPS) are two other products of fermentation associated with health-related benefits (Ahmadi Badi et al., 2017; Korcz et al., 2018). It has been indicated that EPS provides several health benefits, including cardioprotection, antiulcer properties, antioxidant properties, and the reduction of cholesterol levels (Das et al., 2014; Hongpattarakere et al., 2012). As well, EPS from *Lactobacillus plantarum* 70810 restricted BGC-823, hepG-2, and HT-29 tumor cell proliferation *in vitro* and were used as antitumor agents (Wang et al., 2014). Similar to probiotics, postbiotics promote broiler growth performance by increasing gene expression of nutrient transporter (galactose transporter, glucose transporter dependent on Na⁺ and long-chain of acyl CoA dehydrogenase genes; Faseleh Jahromi et al., 2016). Among antimicrobial metabolites of postbiotics, organic acids, and bacteriocins exhibit the ability to reduce the pH and pathogens' proliferation in the gut (Aguilar-Toalá et al., 2018).

Immunological Response of Postbiotics

According to several investigations, postbiotics have been found to exert immunomodulatory effects similar to those of probiotics. The cell-free supernatant derived from *L. reuteri* DSM 17938 exhibited an upregulation in the synthesis of IL-10, which is a postbiotic cytokine known for its anti-inflammatory properties. IL-10 plays a crucial role in modulating the immune system by influencing the function of retinoic acid-driven mucosa-like dendritic cells. This upregulation of IL-10 production resulted in subsequent positive effects on T regulatory cells (Haileselassie et al., 2016). Postbiotics have been linked to immunomodulatory activities because they support the innate and adaptive immune systems, protect the intestinal mucosal barrier, and inhibit the growth of pathogens with antimicrobial compounds (De Marco et al., 2018). Lactobacilli postbiotics, comprising pili and protein p40/p75, have been shown to protect the intestinal barrier, stimulate the production of aggregation factor, bacteriocins, and S-layer proteins, and aid in the killing of pathogens (Teame et al., 2020). Different amounts of lipoteichoic acid (LTA) and peptidoglycan, components of bacterial cell walls, may influence their

immunostimulant activity. It's possible that these bacteria immunomodulate by upregulating Th1 cytokines and downregulating Th2 cytokines (Ou et al., 2011). Postbiotics produced from *Streptococcus thermophilus* may protect the stomach mucosa and boost the body's natural anti-inflammatory response by influencing IL-8 production (Marcial et al., 2017). The research findings revealed that postbiotics, generated after the inactivation of probiotics, exhibited a significantly greater immunomodulatory effect compared to probiotics (de Almada et al., 2016). Abd El-Ghany et al. (2022) results showed that feed and water treatments with the postbiotic compound significantly ($p < 0.05$) improved disease prognosis, growth performance, immune response, bursa of Fabricius/body weight ratio, and intestinal coliform count in challenged chickens. Finally, the postbiotic substance in a dry or liquid form improves the health, performance, and immunity of colisepticaemic broiler chickens. Postbiotics and para-probiotics containing a 0.2% active culture of *Lactiplantibacillus plantarum* were developed for use in broiler starter and finisher diets. The level of IgA in the colon mucosa was considerably changed by dietary treatments. Significant fluctuations in plasma IgM levels were seen during the finishing phase. Growth hormone receptor (GHR) and insulin like growth factor 1 (IGF-1) were increased with the use of postbiotics and para-probiotics (Danladi et al., 2022).

A postbiotic product known as *Saccharomyces cerevisiae* fermentation-based postbiotic (SCFP) is made up of functional metabolites that are created using an exclusive *S. cerevisiae* fermentation method. In commercial poultry, it has been reported that this product improves gut health and immune function. This is accomplished by lowering corticosterone levels, heterophil: lymphocyte ratios, and physical asymmetry during stressful events; reducing intestinal lesions and improving immune function during *Eimeria maxima* and *Eimeria tenella* infections; increasing feed conversion, growth rate, meat yield, and egg production; and possibly reducing colonization by foodborne pathogens (Gingerich et al., 2021). Postbiotics have been seen to exert an influence on immunomodulation; nevertheless, further investigation is necessary in order to comprehensively elucidate the mechanisms behind the immunomodulatory qualities exhibited by postbiotics, which represent a notable attribute of these substances. The immunomodulatory effects of postbiotics may be attributed to the presence of several components in their cell walls, including small molecules such as SCFAs, LTA, peptides/proteins, or a combination thereof (Sun et al., 2018; Vinolo et al., 2011).

Mechanism of Action

Postbiotics can act in five different ways (Salminen et al., 2021): (1) Indirectly, postbiotics may transform the microbiota such as by quorum quenching or by carrying quorum sensing molecules (Grandclément et al., 2016) or by having lactic acid, which is used by some microorganisms to produce butyrate and SCFAs, which are helpful in the microbiota (Laverde Gomez et al., 2019). The presence of postbiotic adhesions [e.g., fimbriae (Tytgat et al., 2016) and lectins (Petrova et al., 2016)] can also compete for adhesion sites with resident microbes. (2) Improvement in the function of the intestinal barrier; If sufficient amounts of SCFAs are present in a postbiotic preparation, they may protect against disruptions caused by lipopolysaccharide and alter the functions of epithelial barriers (Feng et al., 2018). (3) Alteration by systemic and local immune responses; At systemic and local levels, immune-modulating activities are typically triggered through molecular patterns associated with microorganisms that interact with certain PRRs of immune cells. These receptors, for example, receptors of nucleotide-binding oligomerization domain, C-type lectins, and Toll-like receptors, are responsible for regulating cytokines and immune responses (Lebeer et al., 2010). (4) Alteration of systemic metabolic response: Enzymes and metabolites on and inside inactivated microorganisms' surface in postbiotics may directly affect systemic metabolic responses. In addition to modulating

the microbiota community structure and interacting with many receptors of the host, bile acids have a variety of downstream effects on metabolic processes in the host, such as lipids, xenobiotics, glucose, and energy metabolism (Long et al., 2017). (5) Systemic signaling through the nervous system; When sufficient amounts of metabolites of microbes such as SCFAs are available in preparation for postbiotic, they release serotonin by stimulating enterochromaffin cells, which then enter the bloodstream (Iwasaki et al., 2019). The Postbiotic’s mechanism of action is given below in Fig. 1. A non-exhaustive list represents some examples of microbial effector molecules mediating these systems. By maintaining postbiotics cellular structure, e.g., by an enhanced affinity for interacting with receptors of the immune system or by improving the time of residence of active molecules within the host, effector molecules’ activity could be better continued. Within the host, the cell wall protects against rapid degradation with the help of digestive enzymes and immune attacks. This condition is similar to the vaccine situation when most pathogenic and toxic parts are deleted or inactivated, but the cellular structure should be preserved.

Another Beneficial Potential

Disturbing gut microbiota, such as pathogen colonization and proliferation of native pathobionts, led to different diseases and gut health issues. From a healing point of view, components of postbiotics inhibit pathogens in the gut by competing for sticking to epithelium and mucosa (Mantziari et al., 2020). Bacteriocin is a tiny antimicrobial peptide that shows inhibitory action against pathogenic organisms. It may prove a valuable candidate as an antimicrobial agent in food and other pharmaceutical applications (Simons et al., 2020; Yang et al., 2014). Postbiotic as a growth promoter lead to improve the host’s

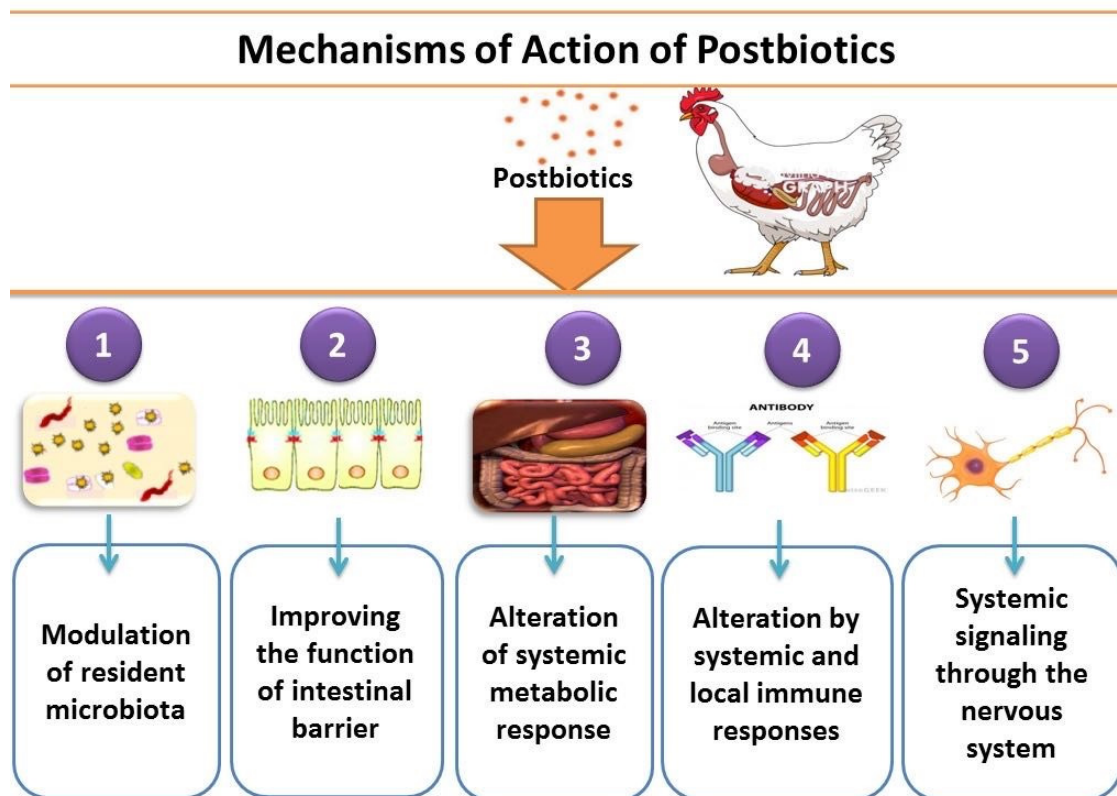


Fig. 1. Mechanisms of action of postbiotics.

health as well as exhibit antimicrobial, antioxidant, immunomodulatory, anti-inflammatory, antiproliferative hypocholesterolemic, and hepatoprotective activity (Aguilar-Toalá et al., 2018). Either alone or in combination, strains of *L. plantarum* are familiar postbiotic producers (Thanh et al., 2009). *L. plantarum* strains exhibited effectiveness in pigs (Loh et al., 2013), rats (Loh et al., 2009), broiler chickens (Faseleh Jahromi et al., 2016; Kareem et al., 2016, Kareem et al., 2017; Loh et al., 2010; Petrof et al., 2004; Thanh et al., 2009). According to Choi et al. (2006), *L. casei*, *L. rhamnosus*, *Lactobacillus brevis*, and *L. acidophilus* with soluble intracellular polysaccharide fraction can be used as anticancer material because of their selection for cancer cells of human, and exert an antioxidative effect in the food industry.

Efficacy of Postbiotics with Another Biotic Family

Among some of the excellent antibiotic alternatives, there are some biotic feed additives, including prebiotics, probiotics, postbiotics, and synbiotics. In addition to improving production and intestinal health and controlling enteric pathogens, they have also been used to relieve problems caused by antibiotics (Faseleh Jahromi et al., 2016).

To heat and oxygen, many probiotic organisms are sensitive; thus, maintaining their stability is a technological challenge, but inanimate microorganisms can be stored for an extended period. During storage and industrial processes, postbiotics possess natural strength, which is their main feature. In geographical regions without reliable cold chains or high ambient temperatures, postbiotics may be more suitable than probiotics for preserving live microorganisms. During the storage of most products with extended shelf life, probiotics mostly die. At the end of their shelf life, it is hard to idealize about dead cells level present in the effects of probiotics, as the rate of death varies depending on storage conditions (oxygen levels, the activity of water, time and temperature, etc.) and physiological characteristics of strain (Huber et al., 2005).

Promising Effects on Other Animals

Izuddin et al. (2019) concluded that postbiotic supplementation improved the weight gain of lamb, feed consumption, nutrient digestibility, and consumption. However, ruminal ammonia-N and butyrate concentrations were enhanced, whereas total VFA and pH were unaffected. Glucose, urea nitrogen, and complete protein in blood were higher in lambs fed postbiotics. The levels of triglycerides and cholesterol in the blood did not differ. Rumen protozoa and methanogens decreased after postbiotic treatment, but fiber-degrading bacteria improved. Expression of mRNA for hepatic IGF-1 and ruminal MCT-1 was also increased by using postbiotics (Izuddin et al., 2019).

Additionally, dietary postbiotics reduced serum lipid peroxidation, enhanced serum and ruminal fluid antioxidant actions, and enzyme production of hepatic antioxidants in postweaning lambs (Izuddin et al., 2020). Moreover, Loh et al. (2009) demonstrated in rats, growth performance and fecal LAB count were increased, while fecal enterobacteria count was decreased when LAB metabolites were administered in drinking water (Loh et al., 2009). But Foo et al. concluded that water consumption may be reduced due to unwanted taste of these metabolites (Foo et al., 2003). Therefore, it was suggested that to remove the undesirable taste of these metabolites, they should be used in powder form (Loh et al., 2009). In mice, inhibitory and anti-proliferative activity in carcinoma cells of the colon and cell lines, programmed cell death was demonstrated when the sonicated *L. casei* cell suspensions were administered (Tiptiri-Kourpeti et al., 2016). However, in post-weaning piglets, *Lactobacillus plantarum* could enhance growth performance, an environment of gut health, and digestibility of proteins when 0.5% metabolite combinations are administered in feed. He also revealed that in piglets, along with increasing parameters of growth performance, such as overall and average weight gain per day and birth weight, *L. plantarum* liquid metabolites also

reduced the production of diarrhea (Loh et al., 2013).

Promising Advantages in the Poultry Industry

As feed additives, postbiotics can be used to improve the performance of growth and health in broilers (Kareem et al., 2017) and in layers (Choe et al., 2012; Loh et al., 2014). In poultry under heat stress, postbiotics containing *L. plantarum* exhibit antioxidative activities (Humam et al., 2019). Additionally, these metabolites improved the quality of the egg and reduced cholesterol levels of yolk and plasma in layers (Loh et al., 2014). Adding prebiotics and postbiotics containing inulin to broiler chicken rations improved the feed efficiency and total body weight of the birds and sustained growth factor1, mRNA expression of GHRs, and intestinal mucosal structure (Kareem et al., 2016). Even under heat stress conditions, postbiotics produced by *L. plantarum* in the feed of broiler chickens showed better maintenance of gut microbiota, the performance of growth, and intestinal morphology (Humam et al., 2019). Postbiotics and insulin together increased IL-6 mRNA expression in broiler chickens and reduced IFN expression and α -gene expression in tumor necrosis factor-induced by lipopolysaccharide in broiler chickens (Kareem et al., 2017). Abd El-Ghany et al. (2022) illustrated the effects on immunity, health, growth performance, and broilers' gut status facing colisepticaemia when feeding stabilized non-viable *Lactobacilli* postbiotic. Postbiotic compounds significantly improved the disease picture, enhanced the performance of growth, boosted immune response, improved bursa to body weight ratio, and reduced the count of coliform in the intestine of challenged chickens compared to non-treated chickens (Abd El-Ghany et al., 2022). Compared to challenged groups, Johnson's experiment revealed significant weight gain and reduced lesion scores in postbiotic-treated broilers (Johnson et al., 2019). The results of Kalavathy's experiment demonstrated that supplementing broiler chickens with a mixture of 12 strains of *Lactobacillus* had a positive impact. By reducing the total cholesterol of serum, LDL cholesterol, triglycerides, and abdominal fat, it improved FCR and growth performance (Kalavathy et al., 2003). Comparing control birds to those treated with postbiotics and inulin, Kareem predicted a decrease in drip loss and increased the CIE L* of breast muscle. Most carcass attributes, shear force, and cooking loss did not differ between treatments (Kareem et al., 2015).

As a new feed additive in quail feed, postbiotics can be considered the most effective replacer for AGPs. By modulating the gut microbiota, *Lactobacillus animalis* derived from postbiotics can improve performance and promote quail health. It is possible to balance the gut microbiota of quails by feeding them postbiotic liquid instead of antibiotics (Kareem, 2020). Within the caeca of commercial layers, *Salmonella* Enteritidis can be reduced by the addition of probiotics derived from *S. cerevisiae* fermentation in feed, which could serve as preharvest food safety barriers. The addition of SCFP in layer's feed can help in the decline of *Salmonella* Enteritidis within commercial laying hens ceca. It can also serve as an additional preharvest barrier for the safety of food (Gingerich et al., 2021). Thus, Humam et al. (2019) concluded that in broilers, compared to control groups, postbiotics substantially increased total *Lactobacilli* counts and other beneficial bacteria but reduced *E. coli*, *Salmonella*, and *Enterobacteriaceae* counts. Probiotics, prebiotics, and postbiotics supplementation improve enzyme activity and nitrogen utilization in poultry, which reduces ammonia output. Postbiotics enhance feed efficiency and reduce bird sickness and mortality, reducing the environmental impact of chicken production (Zhang and Kim, 2014). Prebiotics and postbiotics can lessen the ecological implications of chicken production by improving feed efficiency and reducing dung output. Feed is the biggest energy user and emitter in poultry production. Broilers supplemented with probiotics have reduced ammonia emissions, an unpleasant pollutant that poses environmental risks (Jeong and Kim, 2014; Zhang and Kim, 2014). Postbiotics reported many functions and advantages in poultry, as shown in Fig. 2. Different authors

performed experiments by using different inclusion levels of postbiotics, as given below in Table 1.

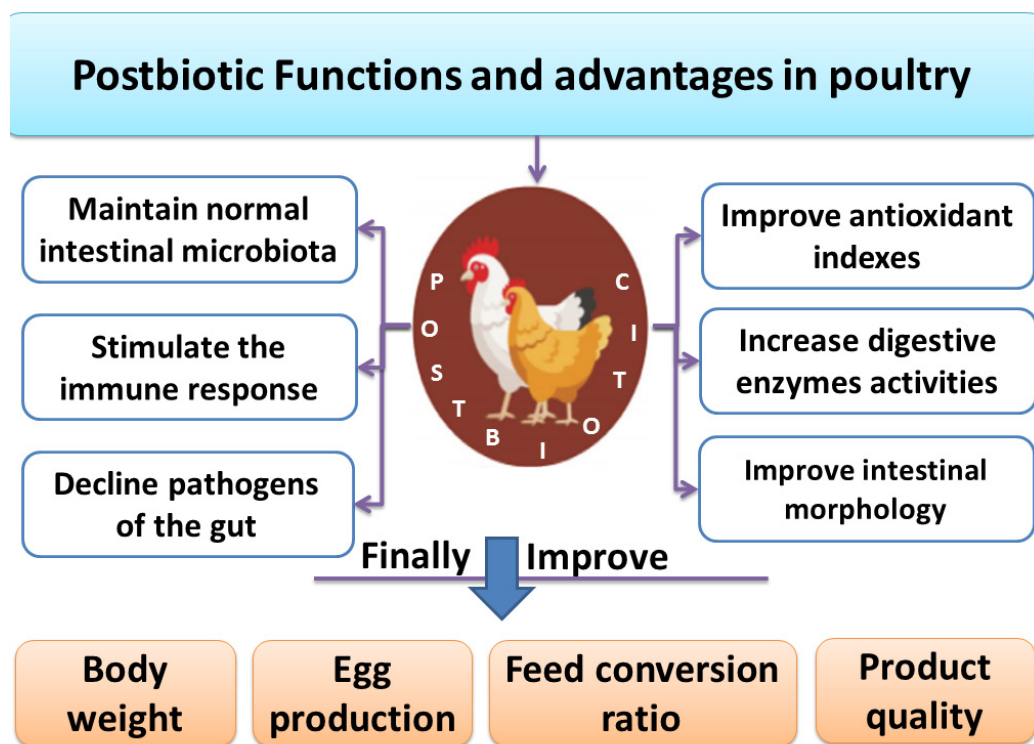


Fig. 2. Postbiotics perform many functions and advantages in poultry.

Table 1. Effects of postbiotics on poultry health and performance (few examples)

S. No.	Postbiotic strain and dose	Species/age	Results	References
1	Postbiotic Culbac® (fermentation product produced by <i>Lactobacillus acidophilus</i> species) Starter diet: 1 kg/ton, grower and finisher diet: 0.5 kg/ton in dry form and in the aqueous form, 4 mL/L drinking water	Broiler chicks 5 wk	- Postbiotic compound either in a dry and/or an aqueous form improved the health, performance, and immunity of colisepticaemic broiler chickens	Abd El-Ghany et al. (2022)
2	0.2% postbiotic and 0.2% paraprobiotic	Broiler chicks 5 wk	- Paraprobiotics and postbiotics revealed a positive influence on the microbiota by supporting the decrease of harmful microbes like the Proteobacteria while increasing beneficial microbes like the Firmicutes. - Paraprobiotics or postbiotics can positively affect the colon mucosa microbiota.	Danladi et al. (2022)
3	0.1% <i>Lactiplantibacillus plantarum</i> postbiotics	Broiler chicks 6 wk	- <i>L. plantarum</i> postbiotic increased growth performance and mucin production, postbiotic ameliorated immune status and tight junction permeability - It improved beneficial bacteria colonization and gut health	Chang et al. (2022)

Table 1. Effects of postbiotics on poultry health and performance (few examples) (continued)

S. No.	Postbiotic strain and dose	Species/age	Results	References
4	1.0% inulin+different levels of postbiotic (0.15%, 0.30%, 0.45%, 0.60%)	Broiler chicks 6 wk	- The level of 1.0% inulin+0.15% postbiotic had the optimal level - Combinations of inulin and postbiotic increased body weight and immune response	
5	0.2%, 0.4%, and 0.6% postbiotic derived from <i>Lactobacillus animalis</i>	Quails 5 wk	- Postbiotic 0.4% increased body weight and body weight gain - Postbiotic promoted the health of quails by modulating gut microbiota	Kareem (2020)
6	Postbiotic product (1 ounce/gallon of fresh water)	Broiler chicks 3 wk	- Postbiotic administration boosts immunomodulatory responses in the gut. - Postbiotic reduces disease pathogenesis following challenge.	Johnson et al. (2019)
7	0.2%, 0.4%, 0.6%, and 0.8% cell-free supernatant (postbiotic: <i>L. plantarum</i> RI11)	Broiler chicks 6 wk	- Postbiotic RI11 augmented plasma glutathione, catalase, and glutathione peroxidase, and boosted zonula occludens-1, mucin 2, IL-10, and mRNA expression. - Postbiotic RI11 declined heat shock protein 70 mRNA expression and plasma tumor necrosis factor alpha, IL-8, alpha-1-acid glycoprotein.	Humam et al. (2019)
8	<i>Saccharomyces cerevisiae</i> fermentation based postbiotic (SCFP) at 1.5 kg/ton (0–21 d) and 1.0 kg/ton (22–32 d)	Layer pullets	- SCFP decreased <i>Salmonella</i> Enteritidis in the Layer Pullet's Ceca. - SCFP decreased the proportion of ceca with enumerable <i>S. Enteritidis</i> .	Gingerich et al. (2021)
9	<i>L. plantarum</i> RG14 and RI11 strains/cell free supernatant	Broilers	- Positively enhanced immune response - Reduced the proinflammatory responses, - Reduced ($p<0.05$) <i>Enterobacteriaceae</i> count.	Kareem et al. (2016)
10	<i>L. plantarum</i> RI11, RG14, and RG11 strains/cell free supernatant (postbiotic component)	Laying hens	- Reduced plasma and yolk cholesterol concentrations	Choe et al. (2012)
11	<i>L. plantarum</i> strains/cell free supernatant (postbiotic component)	Laying hen and broilers	- Reduced faecal <i>Enterobacteriaceae</i>	
12	<i>L. plantarum</i> strains/cell free supernatant (postbiotic component)	Broilers	- Higher growth hormone receptor (GHR) messenger RNA (mRNA)	Thanh et al. (2009)

Beneficial Effects of Postbiotic on Meat and Egg Quality

Because of the use of postbiotics, it is now possible to raise animals, including poultry, without the use of antibiotics, which has resulted in the production of chicken products such as meat and eggs that are both safe and of high quality all over the world. Poultry is raised specifically for the purpose of producing meat all over the world because it is tender, low in fat content, and has a relatively quick production cycle (Haque et al., 2020). Results from Choe et al. (2012) which showed that the plasma cholesterol concentration decreased in eggs that were administered postbiotics. Postbiotics, specifically RI11, have the potential to be used as a substitute for antibiotics and natural sources of antioxidants in heat-stressed broilers.

Postbiotics have also been shown to raise breast meat pH, while simultaneously decreasing shear force and CIE L* (Humam et al., 2019). With the addition of postbiotics to their diets, broiler chickens showed both an improvement in the quality of the meat they produced and a decrease in their plasma cholesterol levels (Choe et al., 2012; Loh et al., 2013). When compared to antibiotics, the effects that postbiotics and inulin had on the quality of the meat were beneficial (Kareem et al., 2015). Poultry replaces vital food animals worldwide, boosting food security, protein supply, and employment (Reuben et al., 2021). This study showed that laying hens benefit from postbiotic metabolite combinations from *Lactobacillus plantarum* strains. All metabolite combinations increased hen-day egg output (Loh et al., 2014). As the world's population grows, so does the demand for meat and eggs. Probiotics/postbiotics may improve their quality. Poultry farming focuses on safe and healthy products. Probiotics improve animal productivity and quality (Hussein et al., 2020).

Conclusion

It is evident from this article that due to the beneficial microbial influence of postbiotics on health, they can be used in food, therapeutic approach, and as AGP replacers when administered in adequate amounts in poultry. Poultry postbiotics improve health, nutrition, and production. They may replace poultry antibiotic growth boosters and other synthetic chemicals. Their gut microbiome, immune system modulation, and pathogen inhibition will ensure safer meat, egg, and eco-friendly production, as well as enormous illness treatment cost reduction and bird loss prevention. Sustainable poultry production with postbiotics will guarantee global food security and safety. There is a need for further research to prevent antibiotic use for disease prevention and to limit the presence of resistant effects among pathogenic bacteria by using postbiotics. Future research on prebiotic-postbiotic interaction may improve quality of the meat and performance or uncover new benefits.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Acknowledgements

This research was supported by the National Key Research and Development Program (2021YFC2103004).

Author Contributions

Formal analysis: Chen H. Writing - original draft: Saeed M, Afzal Z. Writing - review & editing: Saeed M, Afzal Z, Afzal F, Khan RU, Elnesr SS, Alagawany M, Chen H.

Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

References

Abd El-Ghany WA, Fouad H, Quesnell R, Sakai L. 2022. The effect of a postbiotic produced by stabilized non-viable *Lactobacilli* on the health, growth performance, immunity, and gut status of colisepticaemic broiler chickens. Trop Anim

Health Prod 54:286.

- Aguilar-Toalá JE, Garcia-Varela R, Garcia HS, Mata-Haro V, González-Córdova AF, Vallejo-Cordoba B, Hernández-Mendoza A. 2018. Postbiotics: An evolving term within the functional foods field. *Trends Food Sci Technol* 75:105-114.
- Ahmadi Badi S, Moshiri A, Fateh A, Rahimi Jamnani F, Sarshar M, Vaziri F, Siadat SD. 2017. Microbiota-derived extracellular vesicles as new systemic regulators. *Front Microbiol* 8:1610.
- Arain MA, Mei Z, Hassan FU, Saeed M, Alagawany M, Shar AH, Rajput IR. 2018. Lycopene: A natural antioxidant for prevention of heat-induced oxidative stress in poultry. *Worlds Poult Sci J* 74:89-100.
- Arain MA, Nabi F, Marghazani IB, Hassan F, Soomro H, Kalhoro H, Soomro F, Buzdar JA. 2022a. *In ovo* delivery of nutraceuticals improves health status and production performance of poultry birds: A review. *Worlds Poult Sci J* 78:765-788.
- Arain MA, Nabi F, Shah QA, Alagawany M, Fazlani SA, Khalid M, Soomro F, Khand FM, Farag MR. 2022b. The role of early feeding in improving performance and health of poultry: Herbs and their derivatives. *Worlds Poult Sci J* 78:499-513.
- Blacher E, Levy M, Tatrovsky E, Elinav E. 2017. Microbiome-modulated metabolites at the interface of host immunity. *J Immunol* 198:572-580.
- Chang HM, Loh TC, Foo HL, Lim ETC. 2022. *Lactiplantibacillus plantarum* postbiotics: Alternative of antibiotic growth promoter to ameliorate gut health in Broiler chickens. *Front Vet Sci* 9:883324.
- Choe DW, Loh TC, Foo HL, Hair-Bejo M, Awis QS. 2012. Egg production, faecal pH and microbial population, small intestine morphology, and plasma and yolk cholesterol in laying hens given liquid metabolites produced by *Lactobacillus plantarum* strains. *Br Poult Sci* 53:106-115.
- Choi SS, Kim Y, Han KS, You S, Oh S, Kim SH. 2006. Effects of *Lactobacillus* strains on cancer cell proliferation and oxidative stress *in vitro*. *Lett Appl Microbiol* 42:452-458.
- Cicenia A, Santangelo F, Gambardella L, Pallotta L, Iebba V, Scirocco A, Marignani M, Tellan G, Carabotti M, Corazziari ES, Schippa S, Severi C. 2016. Protective role of postbiotic mediators secreted by *Lactobacillus rhamnosus* GG versus lipopolysaccharide-induced damage in human colonic smooth muscle cells. *J Clin Gastroenterol* 50:S140-S144.
- Collado MC, Isolauri E, Salminen S, Sanz Y. 2009. The impact of probiotic on gut health. *Curr Drug Metab* 10:68-78.
- Danladi Y, Loh TC, Foo HL, Akit H, Md Tamrin NA, Naeem Azizi M. 2022. Effects of postbiotics and paraprobiotics as replacements for antibiotics on growth performance, carcass characteristics, small intestine histomorphology, immune status and hepatic growth gene expression in broiler chickens. *Animals* 12:917.
- Das D, Baruah R, Goyal A. 2014. A food additive with prebiotic properties of an α -d-glucan from *Lactobacillus plantarum* DM5. *Int J Biol Macromol* 69:20-26.
- de Almada CN, Almada CN, Martinez RCR, Sant'Ana AS. 2016. Paraprobiotics: Evidences on their ability to modify biological responses, inactivation methods and perspectives on their application in foods. *Trends Food Sci Technol* 58:96-114.
- De Marco S, Sichetti M, Muradyan D, Piccioni M, Traina G, Pagiotti R, Pietrella D. 2018. Probiotic cell-free supernatants exhibited anti-inflammatory and antioxidant activity on human gut epithelial cells and macrophages stimulated with LPS. *Evid Based Complement Alternat Med* 2018:1756308.
- Durso LM, Cook KL. 2014. Impacts of antibiotic use in agriculture: What are the benefits and risks? *Curr Opin Microbiol* 19:37-44.

- Faseleh Jahromi M, Wesam Altaher Y, Shokryazdan P, Ebrahimi R, Ebrahimi M, Idrus Z, Tufarelli V, Liang JB. 2016. Dietary supplementation of a mixture of *Lactobacillus* strains enhances performance of broiler chickens raised under heat stress conditions. *Int J Biometeorol* 60:1099-1110.
- Feng Y, Wang Y, Wang P, Huang Y, Wang F. 2018. Short-chain fatty acids manifest stimulative and protective effects on intestinal barrier function through the inhibition of NLRP3 inflammasome and autophagy. *Cell Physiol Biochem* 49:190-205.
- Foo HL, Loh TC, Lai PW, Lim YZ, Kufli CN, Rusul G. 2003. Effects of adding *Lactobacillus plantarum* I-UL4 metabolites in drinking water of rats. *Pak J Nutr* 2:283-288.
- Gingerich E, Frana T, Logue CM, Smith DP, Pavlidis HO, Chaney WE. 2021. Effect of feeding a postbiotic derived from *Saccharomyces cerevisiae* fermentation as a preharvest food safety hurdle for reducing *Salmonella* Enteritidis in the ceca of layer pullets. *J Food Prot* 84:275-280.
- Gosálbez L, Ramón D. 2015. Probiotics in transition: Novel strategies. *Trends Biotechnol* 33:195-196.
- Grandclément C, Tannières M, Moréra S, Dessaux Y, Faure D. 2016. Quorum quenching: Role in nature and applied developments. *FEMS Microbiol Rev* 40:86-116.
- Haileselassie Y, Navis M, Vu N, Qazi KR, Rethi B, Sverremark-Ekström E. 2016. Postbiotic modulation of retinoic acid imprinted mucosal-like dendritic cells by probiotic *Lactobacillus reuteri* 17938 *in vitro*. *Front Immunol* 7:96.
- Haque MH, Sarker S, Islam MS, Islam MA, Karim MR, Kayesh MEH, Shiddiky MJA, Anwer MS. 2020. Sustainable antibiotic-free broiler meat production: Current trends, challenges, and possibilities in a developing country perspective. *Biology* 9:411.
- Hill C, Guarner F, Reid G, Gibson GR, Merenstein DJ, Pot B, Morelli L, Canani RB, Flint HJ, Salminen S, Calder PC, Sanders ME. 2014. Expert consensus document: The International Scientific Association for probiotics and prebiotics consensus statement on the scope and appropriate use of the term probiotic. *Nat Rev Gastroenterol Hepatol* 11:506-514.
- Homayouni Rad A, Aghebati Maleki L, Samadi Kafil H, Abbasi A. 2021. Postbiotics: A novel strategy in food allergy treatment. *Crit Rev Food Sci Nutr* 61:492-499.
- Hongpattarakere T, Cherntong N, Wichienchot S, Kolida S, Rastall RA. 2012. *In vitro* prebiotic evaluation of exopolysaccharides produced by marine isolated lactic acid bacteria. *Carbohydr Polym* 87:846-852.
- Huber M, Mossmann H, Bessler WG. 2005. Th1-orientated immunological properties of the bacterial extract OM-85-BV. *Eur J Med Res* 10:209-217.
- Humam AM, Loh TC, Foo HL, Samsudin AA, Mustapha NM, Zulkifli I, Izuddin WI. 2019. Effects of feeding different postbiotics produced by *Lactobacillus plantarum* on growth performance, carcass yield, intestinal morphology, gut microbiota composition, immune status, and growth gene expression in broilers under heat stress. *Animals* 9:644.
- Hussein EO, Ahmed SH, Abudabos AM, Suliman GM, Abd El-Hack ME, Swelum AA, Alowaimer AN. 2020. Ameliorative effects of antibiotic-, probiotic- and phytobiotic-supplemented diets on the performance, intestinal health, carcass traits, and meat quality of *Clostridium perfringens*-infected broilers. *Animals* 10:669.
- Iwasaki M, Akiba Y, Kaunitz JD. 2019. Duodenal chemosensing of short-chain fatty acids: Implications for GI diseases. *Curr Gastroenterol Rep* 21:35.
- Izuddin WI, Humam AM, Loh TC, Foo HL, Samsudin AA. 2020. Dietary postbiotic *Lactobacillus plantarum* improves serum and ruminal antioxidant activity and upregulates hepatic antioxidant enzymes and ruminal barrier function in post-weaning lambs. *Antioxidants* 9:250.

- Izuddin WI, Loh TC, Samsudin AA, Foo HL, Humam AM, Shazali N. 2019. Effects of postbiotic supplementation on growth performance, ruminal fermentation and microbial profile, blood metabolite and GHR, IGF-1 and MCT-1 gene expression in post-weaning lambs. *BMC Vet Res* 15:315.
- Jeong JS, Kim IH. 2014. Effect of *Bacillus subtilis* C-3102 spores as a probiotic feed supplement on growth performance, noxious gas emission, and intestinal microflora in broilers. *Poult Sci* 93:3097-3103.
- Johnson CN, Kogut MH, Genovese K, He H, Kazemi S, Arsenaault RJ. 2019. Administration of a postbiotic causes immunomodulatory responses in broiler gut and reduces disease pathogenesis following challenge. *Microorganisms* 7:268.
- Kalavathy R, Abdullah N, Jalaludin S, Ho YW. 2003. Effects of *Lactobacillus* cultures on growth performance, abdominal fat deposition, serum lipids and weight of organs of broiler chickens. *Br Poult Sci* 44:139-144.
- Kareem KY. 2020. Effect of different levels of postbiotic on growth performance, intestinal microbiota count and volatile fatty acids on quail. *Plant Arch* 20:2885-2887.
- Kareem KY, Loh TC, Foo HL, Akit H, Samsudin AA. 2016. Effects of dietary postbiotic and inulin on growth performance, IGF1 and GHR mRNA expression, faecal microbiota and volatile fatty acids in broilers. *BMC Vet Res* 12:163.
- Kareem KY, Loh TC, Foo HL, Asmara SA, Akit H. 2017. Influence of postbiotic RG14 and inulin combination on cecal microbiota, organic acid concentration, and cytokine expression in broiler chickens. *Poult Sci* 96:966-975.
- Kareem KY, Loh TC, Foo HL, Asmara SA, Akit H, Abdulla NR, Ooi MF. 2015. Carcass, meat and bone quality of broiler chickens fed with postbiotic and prebiotic combinations. *Int J Probiotics Prebiotics* 10:23-30.
- Kim HG, Lee SY, Kim NR, Lee HY, Ko MY, Jung BJ, Kim CM, Lee JM, Park JH, Han SH, Chung DK. 2011. *Lactobacillus plantarum* lipoteichoic acid down-regulated *Shigella flexneri* peptidoglycan-induced inflammation. *Mol Immunol* 48:382-391.
- Klemashevich C, Wu C, Howsmon D, Alaniz RC, Lee K, Jayaraman A. 2014. Rational identification of diet-derived postbiotics for improving intestinal microbiota function. *Curr Opin Biotechnol* 26:85-90.
- Konstantinov SR, Kuipers EJ, Peppelenbosch MP. 2013. Functional genomic analyses of the gut microbiota for CRC screening. *Nat Rev Gastroenterol Hepatol* 10:741-745.
- Korc E, Kerényi Z, Varga L. 2018. Dietary fibers, prebiotics, and exopolysaccharides produced by lactic acid bacteria: Potential health benefits with special regard to cholesterol-lowering effects. *Food Funct* 9:3057-3068.
- Laverde Gomez JA, Mukhopadhyaya I, Duncan SH, Louis P, Shaw S, Collie-Duguid E, Crost E, Juge N, Flint HJ. 2019. Formate cross-feeding and cooperative metabolic interactions revealed by transcriptomics in co-cultures of acetogenic and amylolytic human colonic bacteria. *Environ Microbiol* 21:259-271.
- Lebeer S, Claes I, Tytgat HLP, Verhoeven TLA, Marien E, von Ossowski I, Reunanen J, Palva A, de Vos WM, De Keersmaecker SCJ, Vanderleyden J. 2012. Functional analysis of *Lactobacillus rhamnosus* GG pili in relation to adhesion and immunomodulatory interactions with intestinal epithelial cells. *Appl Environ Microbiol* 78:185-193.
- Lebeer S, Vanderleyden J, De Keersmaecker SCJ. 2010. Host interactions of probiotic bacterial surface molecules: Comparison with commensals and pathogens. *Nat Rev Microbiol* 8:171-184.
- Loh TC, Choe DW, Foo HL, Sazili AQ, Bejo MH. 2014. Effects of feeding different postbiotic metabolite combinations produced by *Lactobacillus plantarum* strains on egg quality and production performance, faecal parameters and plasma cholesterol in laying hens. *BMC Vet Res* 10:149.
- Loh TC, Chong SW, Foo HL, Law FL. 2009. Effects on growth performance, faecal microflora and plasma cholesterol after

- supplementation of spray-dried metabolite to postweaning rats. *Czech J Anim Sci* 54:10-16.
- Loh TC, Thanh NT, Foo HL, Hair-Bejo M, Azhar BK. 2010. Feeding of different levels of metabolite combinations produced by *Lactobacillus plantarum* on growth performance, fecal microflora, volatile fatty acids and villi height in broilers. *Anim Sci J* 81:205-214.
- Loh TC, Thu TV, Foo HL, Bejo MH. 2013. Effects of different levels of metabolite combination produced by *Lactobacillus plantarum* on growth performance, diarrhoea, gut environment and digestibility of postweaning piglets. *J Appl Anim Res* 41:200-207.
- Long SL, Gahan CGM, Joyce SA. 2017. Interactions between gut bacteria and bile in health and disease. *Mol Aspects Med* 56:54-65.
- Ma X, Yang Z, Xu T, Qian M, Jiang X, Zhan X, Han X. 2021. Chlortetracycline alters microbiota of gut or faeces in pigs and leads to accumulation and migration of antibiotic resistance genes. *Sci Total Environ* 796:148976.
- Mantziari A, Salminen S, Szajewska H, Malagón-Rojas JN. 2020. Postbiotics against pathogens commonly involved in pediatric infectious diseases. *Microorganisms* 8:1510.
- Marcial G, Villena J, Faller G, Hensel A, de Valdéz GF. 2017. Exopolysaccharide-producing *Streptococcus thermophilus* CRL1190 reduces the inflammatory response caused by *Helicobacter pylori*. *Benef Microbes* 8:451-461.
- Markowiak P, Śliżewska K. 2017. Effects of probiotics, prebiotics, and synbiotics on human health. *Nutrients* 9:1021.
- Matsuguchi T, Takagi A, Matsuzaki T, Nagaoka M, Ishikawa K, Yokokura T, Yoshikai Y. 2003. Lipoteichoic acids from *Lactobacillus* strains elicit strong tumor necrosis factor alpha-inducing activities in macrophages through Toll-like receptor 2. *Clin Diagn Lab Immunol* 10:259-266.
- Nabi F, Arain MA, Hassan F, Umar M, Rajput N, Alagawany M, Syed SF, Soomro J, Somroo F, Liu J. 2020a. Nutraceutical role of selenium nanoparticles in poultry nutrition: A review. *Worlds Poult Sci J* 76:459-471.
- Nabi F, Arain MA, Rajput N, Alagawany M, Soomro J, Umer M, Soomro F, Wang Z, Ye R, Liu J. 2020b. Health benefits of carotenoids and potential application in poultry industry: A review. *J Anim Physiol Anim Nutr* 104:1809-1818.
- O'Grady J, O'Connor EM, Shanahan F. 2019. Dietary fibre in the era of microbiome science. *Aliment Pharmacol Ther* 49:506-515.
- Ou CC, Lin SL, Tsai JJ, Lin MY. 2011. Heat-killed lactic acid bacteria enhance immunomodulatory potential by skewing the immune response toward Th1 polarization. *J Food Sci* 76:M260-M267.
- Patel RM, Denning PW. 2013. Therapeutic use of prebiotics, probiotics, and postbiotics to prevent necrotizing enterocolitis: What is the current evidence? *Clin Perinatol* 40:11-25.
- Petrof EO, Kojima K, Ropeleski MJ, Musch MW, Tao Y, De Simone C, Chang EB. 2004. Probiotics inhibit nuclear factor- κ B and induce heat shock proteins in colonic epithelial cells through proteasome inhibition. *Gastroenterology* 127:1474-1487.
- Petrova MI, Imholz NCE, Verhoeven TLA, Balzarini J, Van Damme EJM, Schols D, Vanderleyden J, Lebeer S. 2016. Lectin-like molecules of *Lactobacillus rhamnosus* GG inhibit pathogenic *Escherichia coli* and *Salmonella* biofilm formation. *PLOS ONE* 11:e0161337.
- Reuben RC, Sarkar SL, Roy PC, Anwar A, Hossain MA, Jahid IK. 2021. Prebiotics, probiotics and postbiotics for sustainable poultry production. *Worlds Poult Sci J* 77:825-882.
- Salminen S, Collado MC, Endo A, Hill C, Lebeer S, Quigley EM, Sanders ME, Shamir R, Swann JR, Szajewska H, Vinderola G. 2021. The International Scientific Association of Probiotics and Prebiotics (ISAPP) consensus statement on

- the definition and scope of postbiotics. *Nat Rev Gastroenterol Hepatol* 18:649-667.
- Sánchez B, Delgado S, Blanco-Míguez A, Lourenço A, Gueimonde M, Margolles A. 2017. Probiotics, gut microbiota, and their influence on host health and disease. *Mol Nutr Food Res* 61:1600240.
- Shenderov BA. 2013. Metabiotics: Novel idea or natural development of probiotic conception. *Microb Ecol Health Dis* 24:20399.
- Shigwedha N, Sichel L, Jia L, Zhang L. 2014. Probiotical cell fragments (PCFs) as “novel nutraceutical ingredients”. *J Biosci Med* 2:43-55.
- Simons A, Alhanout K, Duval RE. 2020. Bacteriocins, antimicrobial peptides from bacterial origin: Overview of their biology and their impact against multidrug-resistant bacteria. *Microorganisms* 8:639.
- Slavin J. 2013. Fiber and prebiotics: Mechanisms and health benefits. *Nutrients* 5:1417-1435.
- Sun M, Wu W, Chen L, Yang W, Huang X, Ma C, Chen F, Xiao Y, Zhao Y, Ma C, Yao S, Carpio VH, Dann SM, Zhao Q, Liu Z, Cong Y. 2018. Microbiota-derived short-chain fatty acids promote Th1 cell IL-10 production to maintain intestinal homeostasis. *Nat Commun* 9:3555.
- Taverniti V, Guglielmetti S. 2011. The immunomodulatory properties of probiotic microorganisms beyond their viability (ghost probiotics: proposal of paraprobiotic concept). *Genes Nutr* 6:261-274.
- Teame T, Wang A, Xie M, Zhang Z, Yang Y, Ding Q, Gao C, Olsen RE, Ran C, Zhou Z. 2020. Paraprobiotics and postbiotics of probiotic *Lactobacilli*, their positive effects on the host and action mechanisms: A review. *Front Nutr* 7:570344.
- Thanh NT, Loh TC, Foo HL, Hair-Bejo M, Azhar BK. 2009. Effects of feeding metabolite combinations produced by *Lactobacillus plantarum* on growth performance, faecal microbial population, small intestine villus height and faecal volatile fatty acids in broilers. *Br Poult Sci* 50:298-306.
- Tiptiri-Kourpeti A, Spyridopoulou K, Santarmaki V, Aindelis G, Tompoulidou E, Lamprianidou EE, Saxami G, Ypsilantis P, Lampri ES, Simopoulos C, Kotsianidis I, Galanis A, Kourkoutas Y, Dimitrellou D, Chlichlia K. 2016. *Lactobacillus casei* exerts anti-proliferative effects accompanied by apoptotic cell death and up-regulation of TRAIL in colon carcinoma cells. *PLOS ONE* 11:e0147960.
- Tsilingiri K, Barbosa T, Penna G, Caprioli F, Sonzogni A, Viale G, Rescigno M. 2012. Probiotic and postbiotic activity in health and disease: Comparison on a novel polarised *ex-vivo* organ culture model. *Gut* 61:1007-1015.
- Tsilingiri K, Rescigno M. 2013. Postbiotics: What else? *Benef Microbes* 4:101-107.
- Tytgat HLP, Douillard FP, Reunanen J, Rasinkangas P, Hendrickx APA, Laine PK, Paulin L, Satokari R, de Vos WM. 2016. *Lactobacillus rhamnosus* GG outcompetes *Enterococcus faecium* via mucus-binding pili: Evidence for a novel and heterospecific probiotic mechanism. *Appl Environ Microbiol* 82:5756-5762.
- Vidal K, Donnet-Hughes A, Granato D. 2002. Lipoteichoic acids from *Lactobacillus johnsonii* strain La1 and *Lactobacillus acidophilus* strain La10 antagonize the responsiveness of human intestinal epithelial HT29 cells to lipopolysaccharide and gram-negative bacteria. *Infect Immun* 70:2057-2064.
- Vinderola G, Sanders ME, Salminen S. 2022. The concept of postbiotics. *Foods* 11:1077.
- Vinolo MAR, Rodrigues HG, Nachbar RT, Curi R. 2011. Regulation of inflammation by short chain fatty acids. *Nutrients* 3:858-876.
- Wang K, Li W, Rui X, Chen X, Jiang M, Dong M. 2014. Characterization of a novel exopolysaccharide with antitumor activity from *Lactobacillus plantarum* 70810. *Int J Biol Macromol* 63:133-139.

- Wegh CAM, Schoterman MHC, Vaughan EE, Belzer C, Benninga MA. 2017. The effect of fiber and prebiotics on children's gastrointestinal disorders and microbiome. *Expert Rev Gastroenterol Hepatol* 11:1031-1045.
- Wu G, Fanzo J, Miller DD, Pingali P, Post M, Steiner JL, Thalacker-Mercer AE. 2014. Production and supply of high-quality food protein for human consumption: Sustainability, challenges, and innovations. *Ann N Y Acad Sci* 1321:1-19.
- Yang SC, Lin CH, Sung CT, Fang JY. 2014. Antibacterial activities of bacteriocins: Application in foods and pharmaceuticals. *Front Microbiol* 5:241.
- Yelin I, Flett KB, Merakou C, Mehrotra P, Stam J, Snesrud E, Hinkle M, Lesho E, McGann P, McAdam AJ, Sandora TJ, Kishony R, Priebe GP. 2019. Genomic and epidemiological evidence of bacterial transmission from probiotic capsule to blood in ICU patients. *Nat Med* 25:1728-1732.
- Yeoman CJ, Chia N, Jeraldo P, Sipos M, Goldenfeld ND, White BA. 2012. The microbiome of the chicken gastrointestinal tract. *Anim Health Res Rev* 13:89-99.
- Zamojska D, Nowak A, Nowak I, Macierzyńska-Piotrowska E. 2021. Probiotics and postbiotics as substitutes of antibiotics in farm animals: A review. *Animals* 11:3431.
- Zendeboodi F, Khorshidian N, Mortazavian AM, da Cruz AG. 2020. Probiotic: Conceptualization from a new approach. *Curr Opin Food Sci* 32:103-123.
- Zhang ZF, Kim IH. 2014. Effects of multistrain probiotics on growth performance, apparent ileal nutrient digestibility, blood characteristics, cecal microbial shedding, and excreta odor contents in broilers. *Poult Sci* 93:364-370.
- Zuidhof MJ, Schneider BL, Carney VL, Korver DR, Robinson FE. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. *Poult Sci* 93:2970-2982.