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REVIEW **Open Access**

Postbiotics: the new horizons of microbial functional bioactive compounds in food preservation and security

Bishwambhar Mishra[1*†], Awdhesh Kumar Mishra[2†], Yugal Kishore Mohanta[3,4*†], Rajasri Yadavalli[1], Dinesh Chand Agrawal[5], Himavarshini Parvath Reddy[1], Rithika Gorrepati[1], C Nagendranatha Reddy[1], Sanjeeb Kumar Mandal[1], Mohammad Zaki Shamim[6] and Jibanjyoti Panda[3]

Abstract
In recent decades, consumers, manufacturers, and researchers have been more interested in functional foods, which include probiotics, prebiotics, and postbiotics. Probiotics are live microbes that, when regulated in enough quantities, provide health benefits on the host, while the prebiotics are substrates that host microorganisms selectively use. Postbiotics are metabolites and cell-wall components that are beneficial to the host and are released by living bacteria or after lysis. Postbiotic dietary supplements are more stable than probiotics and prebiotics. Many bioactivities of postbiotics are unknown or poorly understood. Hence, this study aims to present a synopsis of the regular elements and new developments of the postbiotics including health-promoting effects, production, conceptualization of terms, bioactivities, and applications in the field of food safety and preservation. Postbiotics aid in bio preservation and the reduction of biofilm development in food due to their organic acids, bacteriocins, and other antibacterial activities. The present study examines the production of postbiotic metabolites in situ in food and the effects of external and internal food components. The antimicrobial roles, removal of biofilms, and its applications in preservation and food safety have also been discussed. This paper also explored the various aspects like manipulation of postbiotic composition in the food system and its safety measures.

Keywords Food and health, Food safety, Probiotics, Postbiotics, Bio preservation

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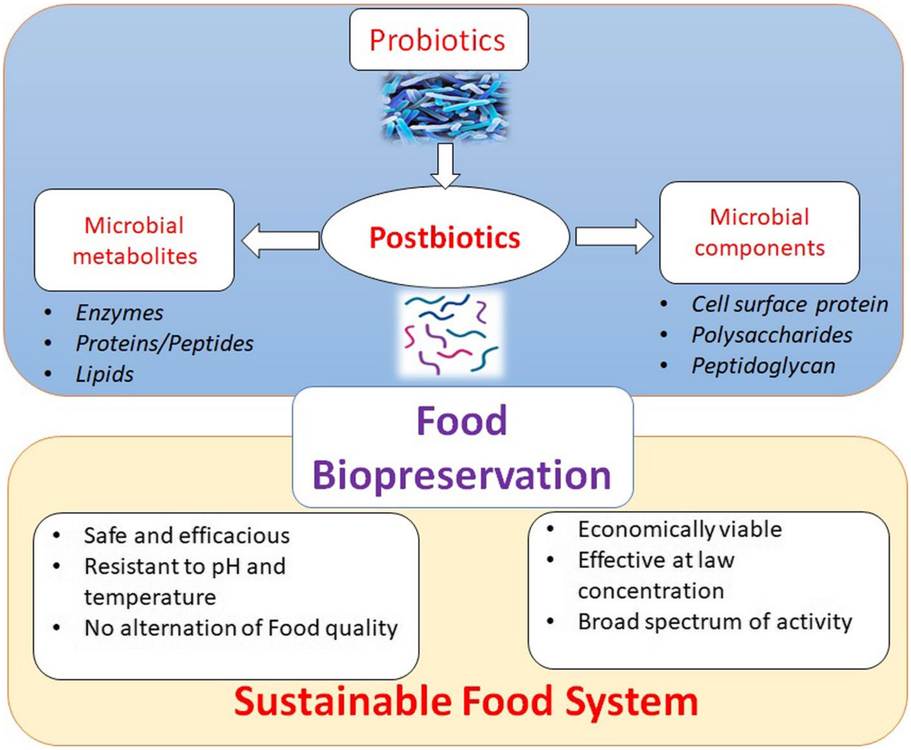
† Bishwambhar Mishra, Awdhesh Kumar Mishra and Yugal Kishore Mohanta contributed equally and treated as joint first authors.

*Correspondence:
Bishwambhar Mishra
mishra.bishwambhar@gmail.com
Yugal Kishore Mohanta
ykmohanta@gmail.com
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Numerous elements, such as physical, chemical, and biological threats, compromise food safety. Biological hazards are of the utmost relevance in this regard. Bacteria, for example, play key roles in food decomposition and food-borne disease transmission. Probiotics and their byproducts are examples of bioactive compounds that can be used to suppress harmful microorganisms growth and thus lengthen the lifespan of food products (Singh et al. 2019). Due to their substantial antibacterial effects, probiotics and postbiotics have been used to prevent the proliferation of pathogenic microorganisms and their mediated corruption. Recent research suggests that postbiotics may be suitable replacement ingredients for the probiotic cells and also can be used as innovative antibacterial agents (Nataraj et al. 2020). Healthy effect and adverse effect of probiotic for host health has been illustrated in Fig. 1.

As per the statement defined by expert group of FAO-WHO 2006, probiotics are "live bacteria, which when provided in suitable proportions, impart a health benefit on the host" (https://www.fao.org/3/a0512e/a0512e.pdf). Moat probiotic supplements contain a finite list of microbial taxa, principally lactic acid bacteria (*Bifidobacterium* spp., *Lactobacillus* spp.), which are considered safe (GRAS). On the other hand prebiotic is defined as "a substrate that is selectively used by host bacteria giving a health advantage" (Binda et al. 2020). Prebiotics can modulate the microbiota framework by boosting species growth, which benefits the host. Synbiotics are frequently characterised as "synergistic mixes of probiotics and prebiotics that benefit the host by enhancing the survival and colonisation of live beneficial bacteria in the host's gastrointestinal tract" (Roberfroid et al. 2010). Synbiotics can modify the configuration of the microbes present in digestive system and the synthesis of microbial metabolites. Postbiotics are any substances that are released by a microorganism or made by it as part of its metabolic process and have a beneficial upshot on the host, directly or the other way. Since postbiotics don't have live microbes, the risks that come with them are lower (Binda et al. 2020; Salminen et al. 2021b). However, one concern that arises in connection with the use of the probiotics is the presence of the antibiotic-resistant genes in certain strains of probiotics (Thorakkattu et al. 2022; Vinderola et al. 2022). This is because these strains can implicit to transport antibiotic-resistant genes

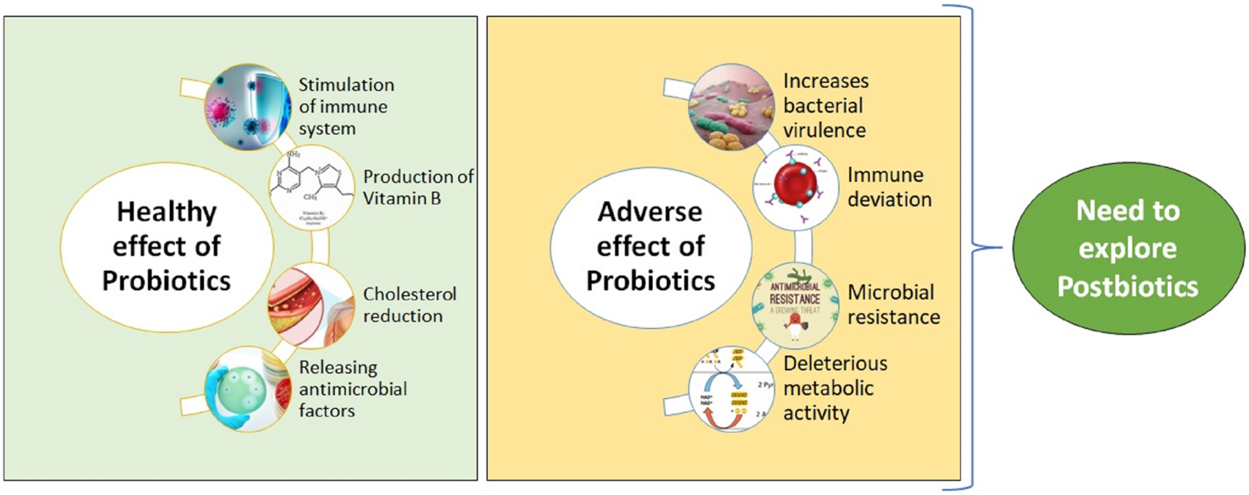


Fig. 1 Healthy effect and adverse effect of probiotic for host health

to infectious microbes through the process of horizontal gene transfer (Puccetti et al. 2020). Because of this lack of stability in the probiotics, the health advantages that are supposed to be offered by probiotic supplements may not be achieved. A significant percentage of postbiotic research is presently devoted to the growth of innovative functional foods and preventive medication formulations for improving host health, also the exact identification of their mechanisms of action. A broad range of bioactive food items, such as probiotics, dairy/ non-dairy products, are currently in the market to meet the needs of clients' nutrition with different dietary choices, especially those who are hypersensitive to milk peptides, lactose intolerance, and vegetarians (Moradi et al. 2020; Ozma et al. 2022; Wegh et al. 2019). Correlation with definition of probiotics, prebiotics, symbiotics, and postbiotics has been illustrated in Fig. 2.

The idea emerged that postbiotics obviate the requirement for conventional intake of substantial quantities of microorganisms (Rad et al. 2021). Also, the use of postbiotics can be done in a controlled and standardized way. However, when living bacteria are used, the level of toxicity is much lower because the size and function of the active structure in the digestive system are directly related to the number of strains and the level of metabolic activity, they show (Aguilar-Toalá et al. 2021; Nataraj et al. 2020; Tsilingiri & Rescigno 2013). Postbiotics have a number of advantages, including greater immunological and digestive health. In addition to having anti-inflammatory, immune-modulating, antioxidant, anti-hypertensive, and anti-obesity, postbiotics also have beneficial qualities. A significant amount of research, encompassing both animal and human trials, has yielded encouraging findings about the efficacy of postbiotics in addressing obesity. For example, studies utilizing kefir products enriched with postbiotics have shown positive effects on body weight, fat mass, and metabolic indicators in both animal models and human subjects. Furthermore,

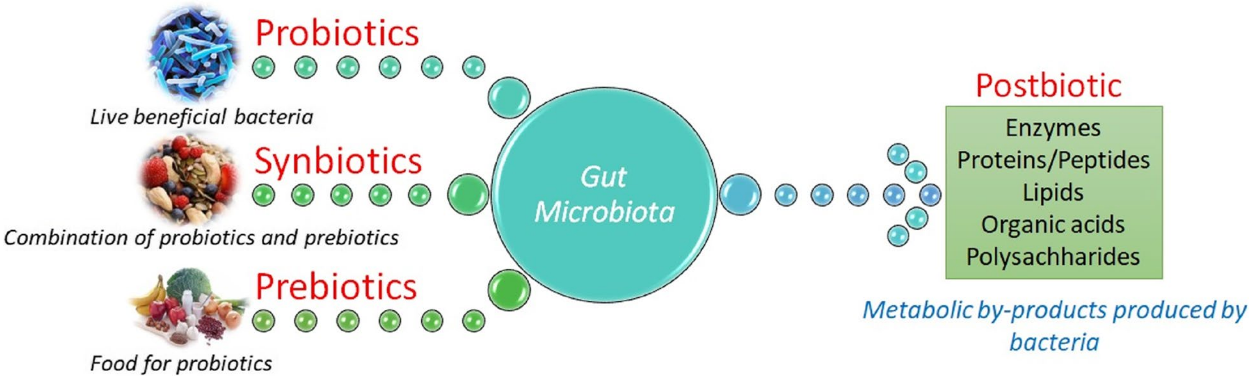


Fig. 2 Differentiating and defining probiotics, prebiotics, symbiotics and postbiotics

empirical research has demonstrated that certain postbiotics possess the ability to regulate the composition of the gut microbiota, hence promoting the proliferation of advantageous bacteria that are linked to the regulation of body weight (Dini & Mancusi 2023; Park et al. 2023).

Postbiotics are appealing for commercial uses due to their non-toxic, easy-to-transport, less expensive-to-store, and up to five-year shelf-lives as well as their cholesterol-lowering and antiproliferative capabilities. Postbiotics such as bacteriocins, organic acids, fatty acids, peptides and H_2O_2 molecules are what give them their antibacterial capabilities. Vitamins produced by probiotic mother strains, especially vitamin C, are helpful in suppressing pathogenic ones. It has a substantial influence on the microbiota structure, the gut ecosystem, barrier function, immune system development, and all of these things. Thus, postbiotics may be useful in management or prevention of a variety of disease entities, including those for which no curative therapy for the underlying cause has yet been identified, such as multiple sclerosis, inflammatory bowel disease or Alzheimer's disease. Clinical studies are being conducted, and the preliminary findings are encouraging. These studies are looking at how to alter the microbiome of people who have the aforementioned diseases (Aguilar-Toalá et al. 2018; Collado et al. 2019; Salminen et al. 2021a). Given the importance of the initial few months of life for the development of the proper microbiota structure, postbiotics can be especially helpful for infants. For the appropriate growth and safeguarding the child's ultimate welfare, the right postbiotic settings for the generation of the right microbiota appear to be required (Ashraf & Shah 2014; Johnson et al. 2019). Postbiotics may be beneficial for the avoidance and treating of SARS-CoV-2 infections because the morphology and metabolic functions of the gut microbiome can be connected with the emergence of the biomarkers that anticipate the course of extreme coronavirus disease- 2019 (COVID-19) (Rather et al. 2021).

The food industry has always been focused on using preservatives to enhance quality and prolong its shelf life. However, most people today dislike food additives because they think they are unhealthy, despite the fact that they don't know how the additives have on health. Because of this, modern research has been trying to come up with products which uses lesser additives or natural ingredients to make sure food is safe and of good quality while still meeting consumer needs. In this way, researchers have paid a lot of attention to natural antimicrobial agents, which have made it possible for manufacturers to switch from using artificial additives and make safer and healthier foods. Several Lactic acid bacterial strains can be thought of as probiotics, and their postbiotic substances often have the same or similar health benefits for consumers. Postbiotics can be used to maintain and eradicate bacterial biofilm formation in foods as well as for food bio-preservation (Motalebi Moghanjougi et al. 2020; Silva et al. 2018). The idea behind the postbiotics covers the microbial fragments and their metabolites that have a positive impact on the host. Due to different architectural and heterogeneity, a variety of possible acquisition methods is implied by the postbiotics. Bacterial cells can be lysed by mechanical or chemical means. These techniques include heat, sonication, solvent extraction, and enzyme extraction. To seggregate and recognize desired compounds, chromatography, dialysis, and extraction are employed (Fiore et al. 2020; Wegh et al. 2019). The current research investigates the formation of postbiotic metabolites in food, in situ, as well as the effects of both the external and the internal components of food. In addition to this, the antibacterial roles, the elimination of biofilms, and all of its uses in food standards and storage have been considered. This review, however, was meant to focus on the very recent uses of postbiotics to ensure food safety. The possible usage of postbiotics in food packaging, food biopreservation and preventing and getting rid of biofilm that comes from food were looked at. This study also investigated a variety of other topics, such as the combination of postbiotic composition in the food system and the precautions that should be taken with regard to it.

Production of postbiotics

The food that is most frequently used to provide probiotics is yoghurt. Numerous products, both fermented (like yoghurt and cheese) and non-fermented (such as cereal and chocolate bars), have probiotics added to them. Certain food characteristics, such as acidity, water activity, specific chemical components, moisture, temperature, package permeability to oxygen, and duration, can pose challenges for probiotics in terms of survival during both production and storage. Most of the stated health advantages of fermented milk have been verified. Another example of a food that provides probiotics, prebiotics, symbiotics, and postbiotics is infant formula (Aguilar-Toalá et al. 2018; Damián et al. 2022). Fermented infant formula has been made specifically using *Bifidobacterium breve* and *Streptococcus thermophilus*. The bacteria are then killed by spray drying following the fermentation process. Inanimate bacteria and fermentation byproducts are present in the newborn formula. A number of pediatric clinical studies showed its safety and postbiotic properties, including modulating the gut microbes to be more similar to that of infants under breastfeeding, reducing the grievousness of severe diarrhea, improving immune markers and inflammatory, which may be connected to few attributes of the gastrointestinal tolerance, and reducing digestive symptoms. Apart from the above, it reduces allergic reactions in babies, as well as the prevention of thymus enlargement and alkaline stools in healthy-term infants (Chaluvadi et al. 2015; Cristofori et al. 2021; Maguire & Maguire 2019). Food supplements are a viable sector for the creation of new postbiotic products since they may have longer shelf lives than probiotic food supplements due to their lack of viability. The range of microorganisms used for functional purposes will probably expand as a result of the idea of postbiotics. Species beyond those from the usually benign genus Bifidobacterium or the family Lactobacillaceae, that were unable to be managed live due to safety and health issues, have been examined as potential postbiotics (Chang et al. 2021; Foo et al. 2019; Liu et al. 2020). Postbiotics can be included in foods and ingredients prior to heat processing without impairing their functions because they are stable throughout a wide range of temperatures. Producers might benefit from this in terms of technology and finances. Postbiotics can be employed in drug carriers such as food supplements and/or pharmacological items since their correct dose can be managed during manufacturing and storing parameters when survivability is not the key deciding factor (Wegh et al. 2019). The production of postbiotics involves several techniques, including sonication, enzymatic treatments, and chemical processes. These methods play a crucial role in extracting bioactive components, modifying microbial structures, and ensuring the viability and effectiveness of postbiotics for various health-promoting applications. The choice of method for postbiotic production depends on various factors, including the desired postbiotic compound, the microbial strain used, the intended application, and scalability considerations. Researchers and manufacturers carefully select the most suitable method to maximize the yield, quality, and safety of postbiotic products. Production of postbiotics through various techniques has been illustrated in Fig. 3.

The most common postbiotic source in the food sector is fermentation. Many milk-based products, as well as other items including kefir, kombucha, yoghurt, and pickled vegetables, naturally contain postbiotics. The producer strains, which can be utilized to extract the postbiotics in situ, primarily consist of *Lactobacillus* and *Bifidobacterium* strains, but they may also contain *Streptococcus*, *Akkermansiamuciniphila*, *Eubacateriumhallii*, *Faecalibacterium*, and *Saccharomyces boulardii* (Gezginç Et Al. 2022; Hernández-Granados & Franco-Robles 2020; Żółkiewicz et al. 2020). A variety of bacteriocins have also been discovered, described, and may have future industrial applications. The microbiological strains and growth parameters will influence their extraction and characterisation. Nisin, also used as a preservative substance in numerous food products (canned soups, dairy products, infant formula), can be made by *Lactococcus lactis*, however they must first be physiologically inert before being transformed to become active (Basavanna & Prapulla 2013). A number of research have also concentrated on using enzymes rather than probiotic bacteria

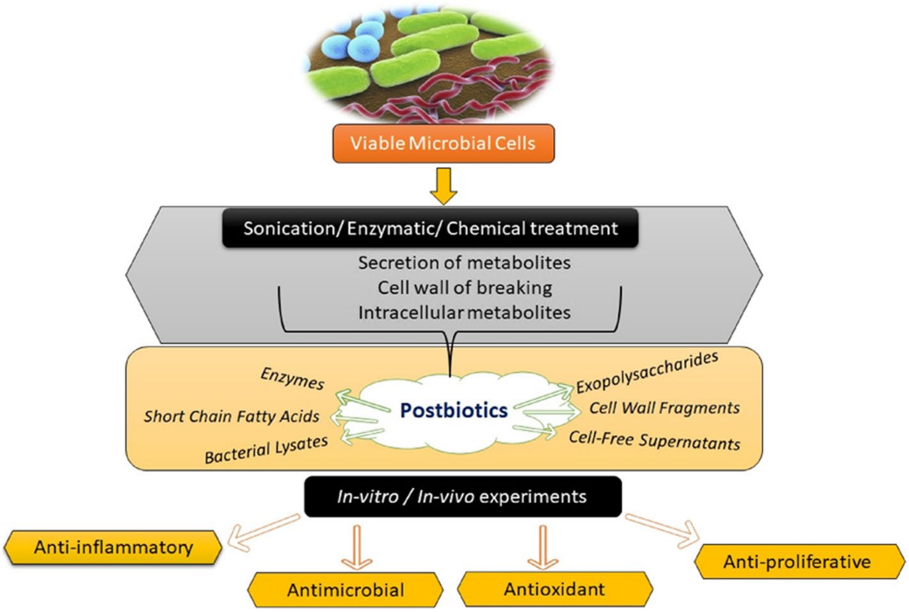


Fig. 3 Schematic representation for production of postbiotics through various techniques and its bioactivities

to produce particular results. *Bifidobacterium pseudocatenulatum* and *Bifidobacterium longum* producing postbiotic enzymes like purified phytases, for instance, increased myoinositol triphosphate levels while reducing the amount of phytates in cereal combinations. Numerous writers have also reported vitamin enrichment in food products. It's a very frequent practice to use fermentation to increase vitamin B content in cereal grains. Vitamin B is abundant in cereal grains. These vitamins, however, are lost during grinding or heat processing. The number of bacteria which can create the vitamins B1, B2, B3, B9, B11, and B12 is increased by cereal fermentation and LAB (Lactic Acid Bacteria) pre-treatment. The LAB fermentation of cereals consequentially enhanced the amounts of protein fractions, total lysine, soluble dietary fiber, sugars and Fe, Ca, and Zn bioavailability in vitro. Additionally, wheat could yield antioxidant peptides, -aminobutyric acid, and angiotensin I-converting enzyme-inhibitory peptides through LAB fermentation (Khalil et al. 2018; Kumar et al. 2017; Masuda et al. 2012).

Postbiotic and food additive interactions

Impact of nutritional factors on postbiotic

The performance of postbiotics is influenced by both internal (matrix substances: food composition, pH levels, moisture content) and external (all elements affecting the storage of food: temperature, oxygen exposure, light exposure, time and duration, packaging materials) factors of food (Patil et al. 2019). The findings of the studies have demonstrated that these variables have a major impact on the structure, nature, and functions of postbiotics, that is important when evaluating the ideal circumstances for their manufacture and use in pharmaceutical or food products (Rad et al. 2021).

Internal factors

The function of postbiotics can be impacted by a variety of food additives like preservatives, emulsifiers and stabilizers, sweeteners, colorants and flavors, and antioxidant etc. The function of metabolites can be inhibited by interactions between active postbiotic metabolites and specific food components such enzymes, proteins, carbs, endogenous microflora, and lipids (Rad et al. 2021). As an illustration, food-borne proteolytic enzymes may influence the activity of postbiotic substances (Peluzio et al. 2021). In order to prevent postbiotic protein molecules from functioning, proteolytic enzymes can degrade them. Either the feed itself contains these enzymes or the proteolytic bacteria in the diet produce them. Trypsin, chymotrypsin, pepsin, papain, and proteinase K are the most crucial enzymes (Abdulhussain Kareem & Razavi 2020). The protease enzyme, for instance, breaks down the protein when proteinaceous postbiotics are used, preventing the postbiotic action. Proteolytic enzymes should therefore be taken into account when talking about postbiotic dysfunctions. Fermented dairy products (e.g., Yogurt and Kefir), fermented vegetables (e.g., Sauerkraut and Kimchi), fermented soy products (e.g., Miso and Tempeh), fermented grain products (e.g., Sourdough Bread) are the examples of foods where enzymatic activity can indirectly promote a favorable environment for postbiotic production. However, there are no examples of postbiotic combinations with dietary components having synergistic or antagonistic effect (Nataraj et al. 2020).

External factors

The antibacterial action of postbiotics can be impacted by food pH. Foods that are acidic or alkaline can make postbiotics less effective (Ebrahimi et al. 2021). Postbiotic activity has a specific range of application. The ideal pH range for postbiotic action is between 4 and 9 (Prabhurajeshwar & Chandrakanth 2017). Pasteurized milk and ground beef were few of the food components which used postbiotics to manage microorganisms because they had good pH levels and no postbiotic function disturbances. Another external element that may have an impact on postbiotic performance is heat. Postbiotics' ability to fight against microbes can be hampered by heat. Postbiotic chemicals' antibacterial action is diminished for 30 min at 30 °C and then for 15 min at 121 °C (Chelliah et al. 2016). As a result, food heating can also have a big impact on the activity of postbiotics. In this instance, maintaining the temperature parameter at an ideal level, is very crucial (Pavli et al. 2018).

Different classes of postbiotics and its bioactivities

The postbiotics can be classified based upon its chemical nature and its bioactivities. Various types of postbiotics and its role in food preservation have been discussed in this section. A synopsis of the few studies that have been reported on postbiotics and their use in a variety of food products has been describes in Table 1.

Organic acids

Inhibiting food spoilage bacteria is one among the most significant effects induced of postbiotics in the food sector. Compounds suitable for use as antibacterial agents include organic acids. One of the important postbiotics is recognized to be organic acids. Two isomers of lactic acid, L and D, which are formed by bacterial fermentation processes, efficiently limit pathogenicity. Additionally, by generating an acidic environment, acids like acetic acid and citric acid prevent the formation of infections. Acetic acids (pka = 4.76) and Lactic acids (pka = 3.86) among organic acids prevent the growth of infections by lowering pH levels in in vivo or/and in vitro condition. Organic

Table 1 Summary of few reported studies in postbiotics and their applications in different food products

S.L No	Name of the food	Postbiotic element	Source organism	Key finding	References
1	Yoghurts	Polysaccharide	*Lactariusvolemus*	Increased water absorption and pH reduction	(Huang et al. 2020)
2	Soybeans	Extracellular products	*Lactobacillus plantarum* YML 007	Shelf life has been extended to two months	(Rather et al. 2014)
3	Cheddar cheese	Exopolysaccharide	*Lactobacillus rhamnosus*	enhanced product functionality	(Torino et al. 2015)
4	Cereal mixtures	Purified physates	*Bifidobacterium longum*, *Bifidobacterium pseudocatenulatum*	Decreased physate concentration and raised myo-inositol triphosphate levels	(Tamayo-Ramos et al. 2012)
5	Cheddar cheese	Unknown enzyme	*Lactobacillus rhamnosus* S93	Increased levels of soluble nitrogen in phosphotungstatic acid and free amino acids	(Azarnia et al. 2010)
6	Grilled beef	Extracellular products	*Lactobacillus sakei* NRRL B-1917	Decreased number of *Listeria monocytogenes* and *E. coli*	(Beristain-Bauza et al. 2017)
7	Custard cream	Bacteriocin	*Lactobacillus gasseri* LA39	Four decomposition strains are completely inhibited	(Nakamura et al. 2013)
8	Food in general	Bacteriocin	*Lactobacillus coryniformis* MXJ 32	Bactericide for *Staphylococcus aureus* and *Escherichia coli*	(Lü et al. 2014)
9	Chicken breast	inhibitor Substance like- Bacteriocin	*Lactobacillus plantarum* ST16Pa	Bioconservative against *Enterococcus faecium* for 7 days	(Da Silva Sabo et al. 2017)
10	Ground beef and whole milk	Pirrolo [1,2-a] and pyrazine-1,4-dione	*Lactobacillus salivarius*	Biofilm removal of *Listeria monocytogenes*	(Moradi et al. 2019)
11	Kombucha Tea	Polyphenols	*Acetic acid bacteria and yeast*	Improved antioxidant properties and anti-inflammatory effects	(Jayabalan et al. 2014)
12	Kimchi	Lactic acid Bacteria Metabolites	*Lactobacillus plantarum and Lactobacillus brevis*	Enhanced gut health and immune modulation	(Jung et al. 2011)
13	Miso soup	Peptidoglycans and Teichoic Acids	*Saccharomyces cerevisiae and Lactobacillus sakei*	Regulation of gut microbiota and anti-inflammatory effects	(Fukuda et al. 2011)
14	Fermented pickles	Organic Acids (e.g., Lactic Acid)	*Lactobacillus plantarum and Pediococcus pentosaceus*	Improved digestion and nutrient absorption	(Marco et al. 2017)
15	Tempeh	Oligosaccharides and Peptides	*Rhizopus oligosporus*	Prebiotic effects, promoting the growth of beneficial gut bacteria	(Ahnan-Winarno et al. 2021)
16	Natto	Nattokinase (Fibrinolytic Enzyme)	*Bacillus subtilis* var. *natto*	Cardiovascular health improvement and blood clot prevention	(Chen et al. 2018)
17	Fermented Dairy products	Bacteriocins and Organic Acids	Various Lactic Acid Bacteria Strains	Enhanced shelf life and inhibition of harmful bacteria	(Guillemard et al. 2010)
18	Sourdough Bread	Lactic Acid and Phenolic Compounds	*Lactobacillus sanfranciscensis and Candida milleri*	Reduced gluten content and improved digestibility for gluten-sensitive individuals	(Papadimitriou et al. 2019)
19	Sauerkraut	Glucosinolates and Isothiocyanates	*Lactic Acid Bacteria*	Anticancer properties and immune system support	(Vitali et al. 2012)
20	Fermented Fish Sauce	Amino Acids and Peptides	Various Marine Bacteria and Yeasts	Rich source of umami flavor and potential antimicrobial effects	(Faisal et al. 2015)

Table 1 (continued)

S.L No	Name of the food	Postbiotic element	Source organism	Key finding	References
21	Kimchi	Bioactive soluble byproducts	*Leuconostoc mesenteroides J.27*	*Leu. mesenteroides* (LAB J.27) and food-grade EO (eugenol or thymol) was highly effective against a variety of pathogenic bacteria	(Toushik et al. 2022)
22	Frankfurters	Bacteriocin	*Pediococcus acidilactici*	Antimicrobial effect against *Escherichia coli, Salmonella*, *Typhimurium*, *Listeria monocytogenes* on frankfurters during refrigerated storage	(İncili et al. 2022)
23	Korean kimchi	Biopreservative	*Lb. plantarum YML 007*	Cell free supernatant improved shel life of unshelled soybeans upto 2 months	(Malashree et al. 2019)
24	Baker's yeast	vitamins, polyphenols, sterols, and phospholipids	*Saccharomyces cerevisiae*	EpiCor is an immunogen product	(Bourebaba et al. 2022; Jensen et al. 2007)
25	Traditional koumiss	Whole peptidoglycan (WPG)	*Lactobacillus paracasei* sub sp. *paracasei* M5 strain	Potential anticancer activity	(Bourebaba et al. 2022; S. Wang et al. 2018a, b)
26	Breast-milk feeding	Lipoteichoic acid (LTA)	*B. animalis* subsp. *lactis* CECT 8145	Reduces fat deposition	(Balaguer et al. 2022)
27	Yogurt	D-alanyl-lipoteichoic acid	*Lactobacillus plantarum* CRL1506	Modulate the Intestinal Antiviral Innate Immunity	(Mizuno et al. 2020)
28	Tomato processing waste	Exopolysaccharides	*Lactobacillus buchneri* TCP016	Induced liver injury and improves the modification of the gut microbiota	(Xu et al. 2019)
29	Fermented Fuyuan pickle	Exopolysaccharides	*L. fermentum* S1	Promising functional adjunct for application in foods	(Wang et al. 2020)

acids' impact on bacterial cell membranes is connected to their inhibitory action. Decreasing the pH inside the cell and maintaining membrane integrity are the key mechanisms at play here (Chang et al. 2021). There are two connections between organic acids' antibacterial properties preventing or regulating acidification of cellular cytoplasm and energy production. Organic acids (tartaric acid, acetic acid, lactic acid, citric acid, and malic acid) produced by three strains of *Lactobacillus plantarum* (P1, S11, and M7) and looked into how effective these acids were at killing pathogenic bacteria (*Escherichia coli* and *Salmonella*) (Hu et al. 2019). They discovered that *L. plantarum* strains reduce the growth of harmful bacteria by secreting organic acids. Organic acids work to kill bacteria by bringing down their pH and acidifying their cell membranes. Lactic acid and acetic acid are two organic acids that have particularly potent antibacterial properties. These findings suggest that a strategy involving the mixing of various organic acids could be used to generate new antibacterial agents for widespread usage in the food industry (Chelliah et al. 2016; Ebrahimi et al. 2021; Moradi et al. 2021; Patil et al. 2019; Pavli et al. 2018; Peluzio et al. 2021; Prabhurajeshwar & Chandrakanth 2017).

Bacteriocin

Antimicrobial peptides or proteins known as bacteriocins are produced by a variety of bacteria, including *Archaebacteria* and *Eubacteria*. Because of their potent antibacterial properties, bacteriocins have been utilized by humans in fermented meals for countless years. Bacteriocins are classified according to their size, mode of action, and spectrum of inhibitory activity. Bacteriocins offer a variety of advantageous properties, such as the ability to withstand heat and pH changes and to inhibit the development and growth of gastrointestinal infections. The inhibition of spore formation, pore development on pathogenic cell membranes, and impacts on the morphological and functional properties of bacterial peptides are all key components of bacteriocins' antibacterial mechanism (Abdulhussain Kareem and Razavi 2020; Kim et al. 2020). Wang et al. (2018a, b) employed fish-isolated *Lactobacillus plantarum* LPL-1 bacteriocins against *Listeria monocytogenes* in a study (Wang et al. 2018a, b). It was discovered as a result that the bacteriocins might stop *L. monocytogenes* from growing by acidifying its cell membrane and producing pores in the bacterial membrane. Kim et al. (2020) and his colleagues examined the effectiveness of *Lactobacillus taiwanensis* produced bacteriocins against *Escherichia coli* and *Salmonella gallinarum* in a different investigation. As a result, it was discovered that *L. taiwanensis* bacteriocin may destroy pathogenic bacteria's protein structures and impede bacterial development by lysing their membranes. Bacteriocins can be utilized as a technique to reduce the bacteria that can cause food spoiling, according to the findings of the studies listed above (Kim et al. 2020).

Fatty acids

Antibiotics can be replaced with fatty acids and their derivatives. For over a century, it has been recognized that fatty acids possess antibacterial properties. Fatty acids are generated by joining a hydrophilic carboxylic group to a saturated or unsaturated carbon chain. Additionally acknowledged as possible postbiotics with significant antibacterial effects are fatty acids (Patil et al. 2019). Eicosapentaenoic acid (EPA), a long-chain fatty acid, inhibits the growth of Gram-positive bacteria. Lauric and meristic acids, among other fatty acids, have a strong inhibitory effect on the growth and development of microorganisms. Fatty acids have antimicrobial effects on bacteria by causing cell lysis, increased membrane permeability, disruption of the electron transport chain, disruption of enzyme activity and structure, and induction of functional/ morphological alterations in sensible components like proteins. The impact generated by fatty acids induced by *L. fermentum*, *Lactobacillus acidophilus* and *L. paracasei* against *Klebsiella oxytoca* was investigated by Higashi and colleagues in 2020. They discovered that the probiotic bacteria's fatty acids lyse *Klebsiella oxytoca*'s cell wall, preventing *Klebsiella oxytoca* from growing (Higashi et al. 2020).

Peptides

Antimicrobial peptides are produced by microorganisms. Peptides kill microorganisms by inhibiting the synthesis of macromolecules and degrading microbial membranes, which is known as pleiotropic processes. There are two categories of antimicrobial peptides: ribosomal and non-ribosomal. The bacteria's ribosomal proteins exhibit potent antibacterial action in vitro by rupturing microbial membranes. Nearly all bacteria have peptides. As was already noted, some peptides primarily target cell membrane, whereas others target cytoplasm and delicate bacterial structures. The peptides' antimicrobial effects include (a) causing the bacterial cell membrane to become acidic, (b) producing physical holes that allow cells to leak out, (c) generating hydrolases that harm the cell wall, and (d) harming the microorganisms' sensitive internal components. *E. coli* Nissle 1917 peptides were used by Forkus et al. (2017) to combat *Salmonella enterica* that was isolated from digestive system of the turkey. In this work, it was discovered that *Salmonella enterica* growth is inhibited by *E. coli* Nissle 1917 antmicrobial peptides that damage the cell wall. *Bacillus subtilis* produces antibacterial peptides that have been tested for effectiveness against *E. coli* and *L. monocytogenes*. According to the study, *Bacillus subtilis* peptides harm sensitive structures in order to prevent germs from growing. These findings raise the possibility of employing probiotic-produced antimicrobial peptides for food preservation (Forkus et al. 2017; Osés et al. 2015).

Unlike ribosomal peptides, non-ribosomal peptides are produced through non-ribosomal peptide synthetases (NRPS) or polyketide synthases (PKS), complex enzyme systems that are capable of assembling peptides from individual amino acid building blocks. These non-ribosomal peptides can have diverse structures and functions (Enzyme inhibition, immune modulation, and biofilm disruption etc.) including antimicrobial activity (Hernández-Granados and Franco-Robles 2020; Li et al. 2021).

Hydroxyl radicals

H_2O_2 can be converted into hydroxyl radicals, which have potent oxidative properties. All bacteria primarily create hydrogen peroxide, which is the principal metabolite of lactic acid bacteria and is typically found in catalase-negative bacteria under aerobic culture. The inhibitory and antibacterial effects are primarily determined by the concentration of hydrogen peroxide (H_2O_2), which can have variable effects depending on a number of factors. Bacterial concentration can also be influenced by a number of variables, including particular bacterial strains and ambient conditions (temperature and pH). H_2O_2 has powerful oxidizing properties that cause damage to cytoplasmic protein structures in bacteria, which contributes to its antibacterial activities (Li et al. 2021; Markowiak & Ślizewska 2017). The effectiveness of *Bifidobacterium longum, B. infantis, Lactobacillus acidophilus*, and *L. rhamnosus* breve against methicillin-resistant *Staphylococcus aureus* (MRSA*)* in vitro was examined. The research found that hydrogen peroxide produced by probiotic bacteria can reduce the growth of Staphylococcus aureus. According to these findings, postbiotic substances like hydrogen peroxide can be utilized as an effective substitute for antibiotics in the fight against pathogens and spoilage of food (Żółkiewicz et al. 2020).

Vitamins

Large amounts of vitamins are produced by probiotic bacteria in the food matrix and the stomach of the host. Although probiotic bacteria in the colon produce very little vitamin material, food matrix production of vitamins, particularly in dairy products, greatly rises. It was discovered through researching the probiotic bacteria's antibacterial function that the vitamins these bacteria produce are crucial in blocking dangerous germs. Vitamin compounds are created in lab models by breaking down probiotic microorganisms (*Lactobacillus plantarum*). Comparatively, vitamin C plays a stronger antibacterial role. Vitamin C raises the acidity of the lipids in bacterial cell membranes, causing the membrane and cell wall of the bacteria to be lysed. Postbiotic chemicals have valuable antibacterial capabilities, and the food industry can utilize these compounds in a variety of ways to preserve food and lengthen food shelf (Cueva et al. 2010; Górska et al. 2019).

Applications of postbiotics in food biotechnology

Because microbiological deterioration, notably mould growth, starts on the food's surface, it is not practical to cheaply embed a significant amount of the preservative in the matrix of the food because this would result in the food becoming contaminated (Vilela et al. 2018). Use of food packaging to increase food's shelf life has been suggested as a potential solution to these issues.

Bio preservation of food

Dairy products have been used in the past to help the good bacteria in the stomach (probiotics). Probiotic strains might not survive during processing and storage, nevertheless, if extrinsic elements that cause dairy components to degrade have an adverse effect. Including postbiotics in dairy products is a cutting-edge method of enhancing their safety. The preservation of food naturally depends on postbiotic performance characteristics. From a safety standpoint, producing postbiotic compounds in a Mannitol Salt Agar Culture medium is less thrilling than manufacturing postbiotics. For instance, Mehran Moradi et al. researches demonstrated that postbiotics prepared by MRS may show considerable detriment on the product's sensory qualities and affect total customer acceptability. Milk is a substance that can absorb substances that change its colour and consistency because of its whiteness, fluidity, and opacity. In a recent study, postbiotics generated from three probiotic milk strains were assessed as antifungal drugs to inhibit the development of mould in semi-hard cheese and sour cream. Postbiotics were discovered to drastically lower the number of fungi in cheese while possibly having no negative effects on sensory perception. As a spray-form antibacterial agent to prevent dangerous germs, postbiotics have recently been proposed (Moradi et al. 2019).

Multiple studies have shown that postbiotic components are effective in improving the preservation of refrigerated meat. For instance, in a recent study, *Bifidobacterium lactis* Bb-12 is directly added to minced meat, which extended its preservation for up to three months at 4 °C (68). Similarly, *Lactobacillus rhamnosus* EMCC 1105 postbiotics at a concentration of 100 mg/g eliminated *Clostridium perfringens* in minced chicken after four days of storage at 6 °C. The antibacterial action of postbiotic molecules is determined by their type, with bacteriocins being potent antibacterial agents (69). In one study, postbiotics from three probiotics (*Lactobacillus casei* 431, *Lactobacillus acidophilus* LA5, and *Lactobacillus salivarius*) were evaluated for their antibacterial effects on *Listeria monocytogenes* in minced beef and Luria Bertani broth. The postbiotic substance inhibited *L. monocytogenes* and prevented the deterioration of Luria Bertani broth and minced meat (70).

Removal of biofilm

There are a variety of microorganisms with varying rates of growth that may include one or more different types. In a protein or carbohydrate matrix, a complex microbial population is called a biofilm. Microorganisms like bacteria and fungi can generate biofilms (Urish et al. 2016). These abilities are shared by gram-negative and gram-positive bacteria. One of the major problems facing the world today is the bacterial resistance to antimicrobials during the biofilm phase. Reversible and irreversible surface adhesion, microclone forms with exopolysaccharide synthesis, and other production steps are among them. For the food product industry to make ensure food safety, controlling colony components and irreversible biofilms is crucial. The removal of biofilms created by the food industry is less effective when cleaning and disinfecting surfaces (Andrade et al. 2020; Przekwas et al. 2020). Some major bacteria that create biofilms are *Campylobacter jejuni*, *Yersinia enterocolitica Listeria monocytogenes* and *Staphylococcus aureus*. To manage and eliminate bacterial biofilms, a variety of techniques have been employed. An innovative method for removing biofilms is to use postbiotics. It has been found in recent studies that postbiotics can successfully remove bacterial biofilms (Andrade et al. 2020; Przekwas et al. 2020. In a study, probiotic bacteria *Lactobacillus casei* 431, *Lactobacillus acidophilus* LA5, and *Lactobacillus salivarius* were used to cure a biofilm created on polystyrene surfaces by *L. monocytogenes*. It has been discovered that postbiotics inhibit the growth of biofilm. The authors illustrated that the lack of postbiotics containing bacteriocin and organic acids was the primary factor in reducing the biofilm of

L. monocytogenes. Postbiotics are a viable strategy in the food product industry to prevent the development of bacterial biofilm (Sharma et al. 2018; Shi & Zhu 2009).

Development of active food packaging

As consumer preferences and market trends change, one of the most inventive methods of food packaging is called "active packaging" (Ahmed et al. 2017). The primary active packaging strategies target flavours, odours, antimicrobials, antioxidants, moisture, ethylene, carbon dioxide, and those that release CO_2. The shelf life of food is affected by a combination of parameters, includes the food product itself, the packaging material used, and various environmental conditions. An active packaging system known as "antimicrobial active packaging" protects food from microbial decomposition during transportation and storage by adding antimicrobial agents (AAs) of plant, animal, and microbial origin or their metabolites, antimicrobial nanoparticles, etc., in the packaging (Yildirim et al. 2018). Due to various environmental factors that can affect the survival of probiotics in bioactive packaging and the production of antimicrobial substances, such as temperature, relative humidity, light intensity, and amount of moisture in food, the antimicrobial efficacy cannot be accurately predicted. Moreover, the consumption of bacterial cells can alter the thermal, barrier and mechanical characteristics of the packaging material. Because of these aspects, antimicrobial packaging methods (use live bacteria) can use postbiotics.

Application of individual postbiotics

The use of postbiotics produced by various probiotic strains is also possible for food-active packaging. Bacteriocins, bioactive peptides have antibacterial properties, are the most often employed postbiotic metabolites in the food sector (Mohammadi et al. 2022). The development and assessment of bacteriocin-loaded active packaging devices is of great interest to many researchers for the aforementioned reasons. Despite the fact that there are a multitude of bacteriocins, nisin is the one that is very well-known and regularly utilized in the production of antimicrobial drug films. Several different strains of the bacterium *L. lactis* produce it (Silva et al. 2018). The effectiveness of starch halloysite nanocomposite films loaded with pediocin and nisin in inhibiting *Clostridium perfringens* and *Listeria monocytogenes* was assessed for their antimicrobial activity. The findings revealed that while pediocin and nisin had varying degrees of antilisterial activity, nisin had higher levels of antagonistic activity against *Clostridium perfringens*. Furthermore, the presence of halloysite aided in reducing bacteriocin diffusion and improved antimicrobial agent retention in the polymer matrix (Meira et al. 2017).

Another type of isolated individual postbiotic used in the production of antimicrobial films is enterocin, which is produced by various *Enterococcus* species. To create the films mentioned in (Ibarguren et al. 2015), enterocin A, B, and P were combined with gelatin. This demonstrates that. The film loaded with enterocin was effective in inhibiting Listeria monocytogenes, *Staphylococcus aureus,* and *Bacillus cereus*. Furthermore, when both prunin laurate and enterocines were incorporated into the film simultaneously, a synergistic inhibitory effect was observed against these microorganisms. They further noted that the addition of active compounds had no impact on the gelatin films' mechanical, thermal, or barrier properties. Bacteriocins are popular and widely used, but they have a significant drawback that prevents them from being used in all situations: they are expensive to produce and have a low yield.

Application of postbiotics mixture

The solution of postbiotics comprises several physiologically active metabolites that exhibit synergistic antibacterial properties towards both the food products and films (Bali et al. 2016). A suitable antimicrobial agent is postbiotics, and interest in creating antimicrobial agent-infused movies has grown recently. *Lacticaseibacillus rhamnosus* NRRL B-442 (6, 12 or 18 mg/ml) and calcium caseinate films were used in an experiment. The results of their investigation suggested that postbiotics applied at a conc. of 18 mg/mL had antimicrobial activity (Beristain-Bauza et al. 2016). *Staphylococcus aureus*, *E. coli*, *Listeria monocytogenes*, and *Salmonella typhimurium* have all been successfully tested in both movies without having their physical characteristics changed. Postbiotics were added to brown ink coatings, which resulted in coatings with lessened puncture resistance and moisture vapor transport (Beristain-Bauza et al. 2016). Whey protein isolate alginate films were created by and coated with postbiotics from *Lactobacillus Sakei* NRRL B-1917 for the purpose of packaging beef cubes contaminated with *Listeria monocytogenes* or *E. coli*. Following 120 and 36 h of cooling, *Listeria monocytogenes* and *E. coli* displayed corresponding decreases in CFU/g of 1.4 and 2.3 $\log_{10}$. The findings indicated that there were no notable distinctions between the grilled beef samples that underwent packaging and those that did not undergo any packaging at all (Beristain-Bauza et al. 2017).

Through the use of bacterial nanocellulose and postbiotics from *Lactiplantibacillus plantarum*, an antibacterial meat wrap nanopape was created in an experiment (Shafipour Yordshahi et al. 2020). A network with less porosity was produced as a result of the immobilisation of postbiotics on the nanocellulose matrix. It was possible to produce films with strong antimicrobial activity using postbiotics, but doing so might compromise the films' physico-chemical characteristics. Postbiotics must therefore be applied at a concentration that maximizes both their thermomechanical and antibacterial propertiesput forth the hypothesis that the improved storage stability of bacteriocins brought about by their immobilisation on cellulose nanocrystals counteracts the negative effects of postbiotics on the barrier and mechanical properties of starch films (Bagde & Nadanathangam 2019).

Manipulation of postbiotic composition in food

The majority of postbiotic sources in the food industry are obtained through the process of fermentation. Postbiotics are naturally occurring microorganisms that can be found in many dairy products, as well as in kefir, kombucha, yoghurt, and pickled vegetables. The extracellular biopolymers, or EPS, that bacteria produce or exude as they develop. The sensory and physiochemical qualities of products made from food can be improved by EPS produced by LAB, including *Lactobacillus rhamnosus*, a crucial component in dairy products (Nguyen et al. 2020). Numerous research have centered the use of enzymes rather than probiotic microorganisms to achieve desired results. For instance, purified phytases derived from Bifidobacterium longum and *Bifidobacterium pseudocatenulatum* have been found to increase myoinositol triphosphate levels and decrease phytate levels in cereal blends. Food items are supposedly vitamin-enriched, according to numerous authors. It's not unusual to use fermentation to increase the vitamin B content of cereal grains. Vitamin B is abundant in grains used for cereal. These vitamins are lost, though, during grinding or heat processing. Fermenting cereal and pre-treating it with LAB (lactic acid bacteria) can result in producing additional bacteria that are capable of synthesizing vitamins B1, B2, B3, B9, B11, and B12. (Nkhata et al. 2018). The LAB fermentation of cereals significantly improved the Ca, Fe, and Zn's *in-vitro* bioavailability as well as sugars, soluble dietary fiber, total lysine, and protein fractions. Through LAB fermentation, wheat may also generate aminobutyric acid, peptides that protect against oxidation, and peptides that block the angiotensin I-converting enzyme. Using probiotic-induced fermentation to eliminate some potentially harmful food components is another creative way to use probiotics in addition to adding postbiotics to food (Bai et al. 2021).

Safety concerns and future prospects

Numerous studies have offered convincing proof of the advantages of bacteria, especially in the gut. In light of the possible risks and safety concerns, the regulatory requirements for postbiotics and other similar functional meals should be anticipated. Despite the risks associated with foodborne bacteria that have already been mentioned, LAB (lactic acid bacteria) and bifidobacteria, which are considered to be beneficial bacteria, can effectively compete against pathogens and release amino acids (AAs) that enhance the lifespan and safety of food products (Nataraj et al. 2020). Additionally, these bacteria have the power to act as potent barriers to the emergence of pathogens and spoilage-causing microbes. The limitations of probiotics led to the development of the postbiotic idea, a novel approach for functional food ingredients. On the other hand, it might be necessary to take into account the probiotic strains, the type of fermentation, and the safety concerns for consuming postbiotics when producing postbiotics (Anderson 2019; Żółkiewicz et al. 2020). Despite the fact that postbiotic eating is still a new strategy, there is no epidemiological or clinical proof of any dangers. The threat of infection is ostensibly gone, though, because there are no active microbes. Studies in vivo and in vitro investigated how postbiotics affected various cell types, blood parameters, metabolic markers, and intestinal mucosa. In vitro research is expected to be advantageous for studying how commensal and pathogenic microbes interact with the host along with its microbial products. In vivo studies are highly encouraged to confirm the effects of postbiotics in *in-vitro* due to the limited transferability of in vitro research and the possibility of species-specific effects. Numerous animal models for postbiotics, short chain fatty acids, peptides, EPS, vitamins, peptidoglycans, lipopolysaccharides, teichoic acids, and peptidoglycans have all been identified as potential alternative treatments for infectious diseases in the aquaculture system (Nataraj et al. 2020).

The role of the intestinal epithelial barrier as the primary defense mechanism against numerous infections is widely recognized. As a result, leaky gut, also known as a disruption in the gut epithelium barrier's regular operation, can allow a variety of harmful substances and organisms to enter the body. Postbiotics are therefore potential options since any drugs that have the ability to improvise the intestinal barrier can be recognized as health-promoters. Not only do living bacteria in the digestive tract benefit from fermented foods, but so do other beneficial organisms. The byproducts of fermentation may also have positive health effects. Postbiotics maintain host health and may act as a mediator for the positive effects via a number of pathways, but the targeted mode of action is still under study. The use of postbiotics in the right amounts and concentrations has been proven to be safe by a number of studies. Food safety is improved by postbiotics' antibacterial properties. Some of the elements that determine the antibacterial effect of postbiotics inside the foodservice industry include the kind and dosage of postbiotics, the type of food modeling, and the features of the food product. The management of food-infecting bacteria is one of the most significant effects of postbiotics on the food industry (Anderson 2019; Dimidi et al. 2019).

Experts predict that postbiotics will have an effect on how the human body works and offer a fascinating area for future study. New products are being introduced by manufacturers to meet the demands of various customers as the research sector grows. Postbiotics provide an advanced and secure way to supplementally improve gut health because they have fewer storage and shelf-life issues than live probiotics. The potential for meals and beverages based on postbiotics has grown as a result of rising health concerns and the subsequent trend toward functional foods. People understand how important their gut microbiota is and how it affects their overall health. Microbial metabolites have come under scrutiny due to the technological challenges posed by the presence of viable microbial cultures in various foods and beverages, as well as the possibility that they could harm immunocompromised people. The demand for healthier food choices by consumers has caused significant transformations in the food and beverage industries. The market is demonstrating that there is a chance for businesses to include postbiotics in the formulations of their products in order to appeal to more customers (Collado et al. 2019; Salminen et al. 2021b). Not only do postbiotics have many health advantages, but they also serve as emulsifiers, preservatives, and guarantee the stability of the finished product, thereby lowering the need for food additives. Researchers are still attempting to determine how postbiotic production may affect people's health, and there aren't many studies on the advantages of postbiotics. In the majority of recent studies, dietary supplements are compared to pre- and probiotic meal consumption (Aguilar-Toalá et al. 2018; Damián et al. 2022).

Conclusion

In summary, the growing interest with functional foods, including probiotics, prebiotics, and postbiotics, has garnered substantial interest from consumers, manufacturers, and researchers in recent years. Postbiotic dietary supplements are notable for their superior stability in comparison to probiotics and prebiotics, rendering them very promising contenders for diverse applications, particularly in the domains of food safety and preservation across the food chain. The objective of this study, as indicated in the passage, is to offer a thorough examination of postbiotics, encompassing their capacity to enhance health, methods of production, nomenclature, biological activities, and their uses in ensuring food safety and preservation. Postbiotics have been observed to exhibit their efficacy in the field of bio preservation by effectively mitigating the formation of biofilms in food products through the use of organic acids, bacteriocins, and several other antibacterial mechanisms. Moreover, the research investigates the in-situ synthesis of postbiotic metabolites in food and examines the impact of both external and internal food constituents on this phenomenon. This study investigates the antibacterial characteristics of postbiotics and their potential utilization in the preservation of food items, hence leading to an overall improvement in food safety.In general, this study on postbiotics presents a potentially fruitful direction for advancement in the food industry. It presents potential solutions that are in line with consumer preferences for healthier, safer, and more sustainable food products. Additionally, it addresses the intricate challenges associated with food safety and preservation throughout the food supply chain.

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Authors' contributions

Conceptualization, B.M., Y.K.M., A.K.M.; Data curation: B.M, H.P., and R.G.; writing—original draft preparation, B.M., A.K.M., Y.K.M., D.C.A., H.P., and R.G.; writing—review and editing, C.N.R., S.K.M., R.Y., M.Z.S.; visualization, Y.K.M., A.K.M. B.M. All authors have read and agreed to the published version of the manuscript.

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Author details

[1] Department of Biotechnology, Chaitanya Bharathi Institute of Technology (CBIT), Gandipet, Hyderabad, Telangana 500075, India. [2] Department of Biotechnology, Yeungnam University, Gyeongsan Gyeongbuk 38541, Republic of Korea. [3] Nano-Biotechnology and Translational Knowledge Laboratory, Department of Applied Biology, School of Biological Sciences, University of Science and Technology Meghalaya (USTM), Techno City, 9Th Mile, Baridu, Ri-Bhoi, Meghalaya 793101, India. [4] Centre for Herbal Pharmacology and Environmental Sustainability, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam,, Tamil Nadu 603103, India. [5] School of Life & Basic Sciences, Jaipur National University, Jaipur, Rajasthan 302017, India. [6] Department of Food Nutrition and Dietetics, Faculty of Sciences, The Assam Down Town University, Assam 781026, India.

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