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Review

Targeting biofilm resistance in meat production: Postbiotics as a clean-label alternative, a bibliometric analysis review

Shirin Akter [a,b,e,1], Md. Ashikur Rahman [a,b,f,1], Md. Ashrafudoulla [c], A.G.M. Sofi Uddin Mahamud [d], Chowdhury Sanat Anjum Reem [a,b], Md Anamul Hasan Chowdhury [a,b], Meidistria Tandi Rapak [b], Hye-Jeong Yoon [a], Sang-Do Ha [a,b,*]

[a] Food Safety and Regulatory Science, Chung-Ang University, Anseong-Si, Republic of Korea
[b] GreenTech-based Food Safety Research Group, BK21 Four, Food Science and Biotechnology, Chung-Ang University, Anseong, Republic of Korea
[c] Department of Food Science, Center for Food Safety, University of Arkansas System Division of Agriculture, Fayetteville, AR 72704, USA
[d] Department of Microbiology, University of Georgia, Athens, GA 30602, USA
[e] Department of Fisheries and Marine Bioscience, Gopalganj Science and Technology University, Gopalganj, Bangladesh
[f] Bangladesh Fisheries Research Institute, Mymensingh, 2201, Bangladesh

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ABSTRACT

Biofilm-mediated contamination poses a persistent threat in the global meat industry, facilitating the survival of foodborne pathogens and reducing the effectiveness of conventional sanitation methods. This review highlights postbiotics, non-viable microbial derivatives and cellular components, including metabolic byproducts, peptides, organic acids, bacteriocins, biosurfactants, and exopolysaccharides which are emerging as multifunctional agents for biofilm control and meat preservation. Postbiotics exert their effects through diverse mechanisms including disrupting adhesion via surface conditioning and gene suppression, impairing EPS matrix formation by interfering with cyclic-di-GMP signaling, and inducing oxidative and metabolic stress in biofilm-forming cells. Unlike probiotics and prebiotics, postbiotics are stable under harsh processing conditions and deliver immediate antimicrobial action without requiring host interaction. Case studies demonstrate their efficacy in reducing *Listeria monocytogenes, Salmonella* spp., and *Escherichia coli* on meat surfaces, packaging materials, and equipment. In addition to microbial safety, postbiotics contribute to product quality by enhancing lipid stability, protein integrity, and color retention. A VOSviewer-based bibliometric analysis further maps global research trends, thematic evolution, and knowledge gaps in postbiotic applications within meat systems. By integrating bibliometric analysis with mechanistic insights, this review evaluates postbiotics as sustainable tools for biofilm control in the meat industry, while emphasizing the need to overcome challenges related to standardization, delivery systems, and regulatory approval to support their effective adoption in clean-label preservation strategies that safeguard meat safety, quality, and consumer acceptance

Introduction

Meat products play a crucial role in global food security and nutrition, serving as a primary source of essential proteins, vitamins, and minerals (De Smet and Van Hecke, 2024). The safety of meat products is of paramount importance, as contamination can lead to severe public health risks, economic losses, and a decline in consumer confidence (Hussain and Dawson, 2013). Ensuring the microbiological safety of meat requires stringent quality control measures, effective preservation techniques, and innovative antimicrobial strategies (Rebezov et al., 2024).

One of the most persistent challenges in the meat industry is contamination due to biofilm formation. Biofilms are structured microbial communities encased in an extracellular polymeric substance (EPS) matrix that attach to processing surfaces, packaging materials, and equipment (Rahman et al., 2025). The resilience of biofilms poses a

* Corresponding author.
E-mail address: sangdoha@cau.ac.kr (S.-D. Ha).
[1] Contributed equally.

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challenge for elimination and eradication, diminishing the effectiveness of conventional cleaning and sanitization methods and facilitating the persistence of foodborne pathogens such as *Listeria monocytogenes, Salmonella* spp., and *Escherichia coli*, thereby increasing the risk of contamination and spoilage (Oliulla et al., 2024). The economic impact of biofilm formation in the meat industry is substantial, with losses attributed to increased product recalls and sanitation costs, production downtime, and reduced shelf life. Estimates suggest that biofilm-related contamination can lead to annual losses of billions of dollars globally, severely affecting operational efficiency and consumer trust (Ali et al., 2023). Consequently, developing innovative biofilm control strategies is imperative to ensure food safety, extend shelf life, and maintain meat product quality (Rahman et al., 2025).

Postbiotics, defined as non-viable microbial derivatives, including metabolic byproducts, peptides, and cell wall fragments, have emerged as a promising approach for food preservation (Thorakkattu et al., 2022). Unlike probiotics, which must remain viable to exert their functional activity, postbiotics offer enhanced stability and consistent antimicrobial efficacy under industrial processing conditions (Salminen et al., 2021). Notably, postbiotic compounds such as short-chain fatty acids (SCFAs), bacteriocins, exopolysaccharide (EPS), and organic acids exhibit antimicrobial properties that disrupt bacterial adhesion, biofilm maturation, and cellular integrity (Che et al., 2024). In addition to inhibiting biofilm formation, these bioactive substances also enhance food quality by improving lipid stability, preserving protein integrity, and maintaining color retention in meat products (Dong et al., 2024). Given their multifunctional antimicrobial, bioactive, and health-promoting properties, postbiotics represent a sustainable, clean-label alternative to synthetic preservatives for improving meat safety and quality, while also offering potential systemic benefits such as modulation of host physiology and metabolic homeostasis (Khani et al., 2025a, 2025b).

Bibliometric analysis offers a powerful methodological framework to comprehensively assess research advancements in postbiotics and biofilm control within meat production. VOSviewer, a widely recognized tool for bibliometric visualization, enables the construction of co-occurrence networks, bibliographic coupling maps, and research trend visualizations, providing in-depth insights into thematic clusters and the global research distribution (Rahman et al., 2023). This approach facilitates the identification of key research domains, collaborative networks, and emerging trends in the application of postbiotics for meat safety and biofilm inhibition.

Accordingly, this study executes a bibliometric analysis using VOSviewer to systematically map the landscape of postbiotic and biofilm-related research in meat products, drawing data from Scopus over the period 2018–2025. Critical developments, knowledge gaps, and future research directions are elucidated by integrating keyword co-occurrence analysis, bibliographic coupling, and source impact assessments. This review also explores the mechanistic action of postbiotics at the molecular and cellular levels, emphasizing their role in disrupting biofilm formation, modulating microbial metabolism, and enhancing food safety in the meat industry. This study aims to integrate bibliometric mapping with mechanistic analysis to assess the role of postbiotics in biofilm control and meat safety, providing a foundation for their strategic application as sustainable and effective alternatives to conventional antimicrobial strategies in food processing environments.

Bibliometric analysis

VOSviewer, developed in the Netherlands by the Centre for Science and Technology Studies (CWTS) at Leiden University under the leadership of Van Eck and Waltman, is a robust bibliometric mapping software available worldwide through vosviewer.com. It is specifically designed to generate and visualize bibliometric networks, including keyword co-occurrence, citation relationships, and collaboration patterns (Akter et al., 2025; Rahman et al., 2025). Its intuitive and interactive interface makes it particularly effective for analyzing large-scale datasets derived from academic databases, such as Scopus, Web of Science, and PubMed. While databases like Scopus and Web of Science excel in retrieving, indexing, and systematically organizing scholarly literature, VOSviewer specializes in analyzing and mapping connections within these datasets. Scopus and Web of Science are invaluable for conducting systematic literature reviews, tracking citations, and identifying high-impact studies. In contrast, VOSviewer excels in uncovering research trends, clustering thematic areas, and visualizing collaborative networks. In this study, data extracted from Scopus were analyzed using VOSviewer to construct co-occurrence networks, bibliographic coupling maps, and visualizations of research trends. This integrative approach combines the comprehensive coverage of high-quality academic literature with advanced visual analytics, enabling a deeper understanding of global research trends, thematic clusters, and gaps in studies focusing on postbiotics, biofilm formation, and their applications in meat products.

Methods

This review employed a bibliometric approach to systematically analyze global research on postbiotics, biofilm control, and applications in meat products. The analysis was conducted in four stages: literature retrieval, data selection, bibliometric mapping, and interpretive synthesis.

Literature retrieval and inclusion criteria

Relevant publications were retrieved from the Scopus database, chosen for its comprehensive coverage of peer-reviewed journals in food science, microbiology, and biotechnology. The search strategy combined the keywords *"postbiotics" AND "biofilm"* OR *"postbiotics" AND "meat products"*. The search was limited to English-language articles and reviews published between January 2018 and February 2025. Conference papers, book chapters, and non-peer-reviewed sources were excluded to ensure consistency and quality.

The timespan of 2018–2025 was selected because the concept of postbiotics only gained standardized recognition during this period, particularly following the ISAPP consensus definition (Salminen et al., 2021). Earlier publications primarily referred to inactivated probiotics, paraprobiotics, or cell-free extracts without explicitly using the term "postbiotics," which could lead to inconsistencies in bibliometric mapping. Limiting the dataset to this timeframe ensures both recency and relevance, capturing the surge of research on postbiotics in relation to biofilm inhibition and meat product applications.

Data extraction and refinement

The initial search yielded 92 publications. Metadata including author names, affiliations, source titles, abstracts, and references were exported in CSV format for further analysis. Duplicate records and irrelevant articles (e.g., those focusing on probiotics or prebiotics without reference to postbiotics or biofilm mechanisms) were manually screened and removed.

Bibliometric mapping with VOSviewer

Bibliometric analysis was performed using VOSviewer (version 1.6.20), developed by the Centre for Science and Technology Studies (CWTS), Leiden University, the Netherlands. Two complementary mapping approaches were applied:

- **Keyword co-occurrence analysis** to identify thematic clusters and research hotspots.
- **Bibliographic coupling** to evaluate country-level contributions and source impact.

Thresholds for inclusion were set at a minimum of six keyword occurrences for co-occurrence analysis and three documents with at least five citations for bibliographic coupling of sources. Visualization maps

were generated to display clusters, link strengths, and collaborative networks.

Interpretive synthesis

The bibliometric findings were integrated with a narrative review of mechanistic studies, experimental evidence, and case reports on postbiotics in meat preservation. This dual approach provided both a quantitative overview of research trends and a qualitative assessment of mechanistic insights and industrial applications.

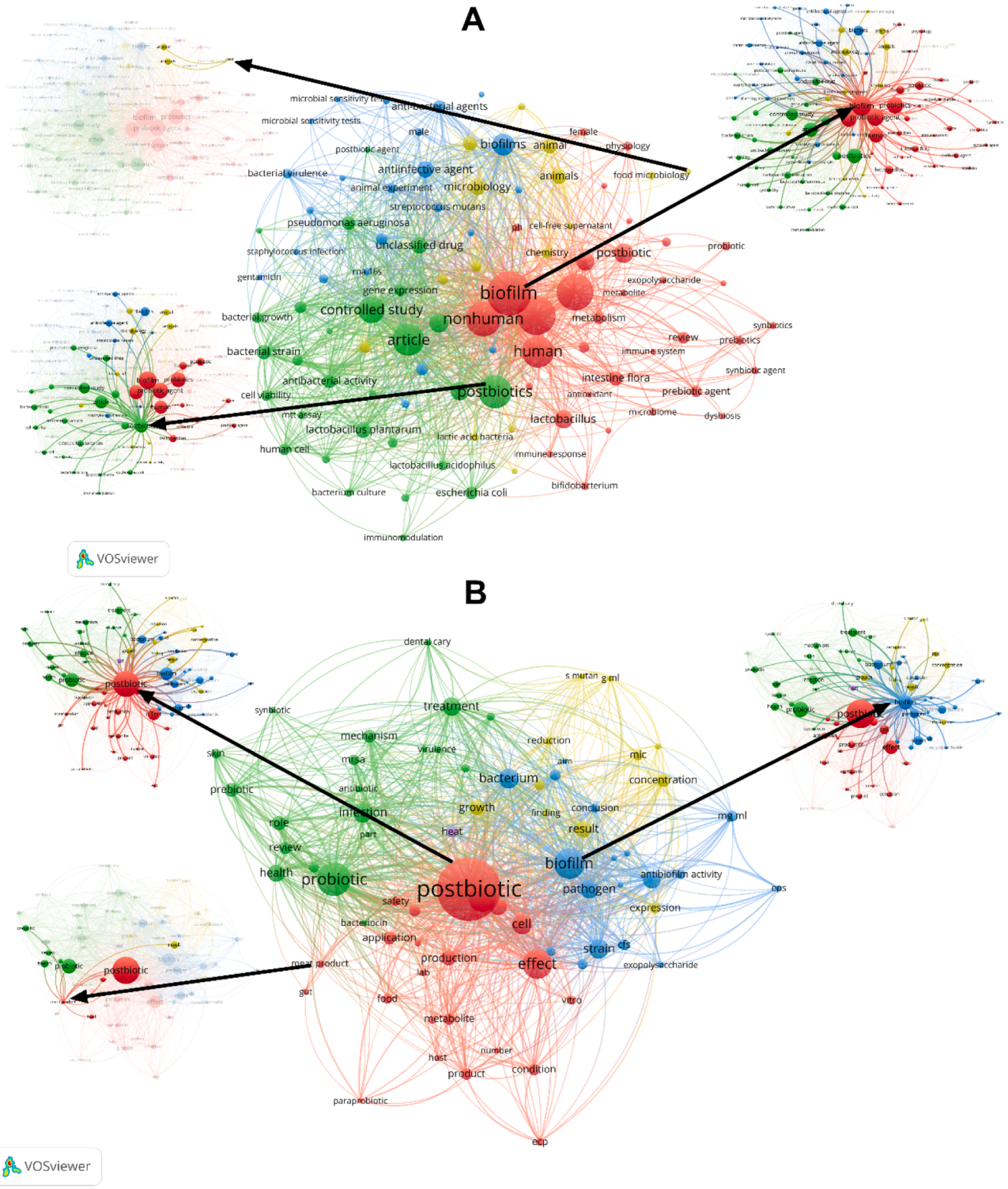


Fig. 1. Network visualization of research trends in biofilm, probiotics, and postbiotics using VOSviewer. (A) and (B) represent two different bibliometric analyses, highlighting the relationships between key terms in literature. The size of the nodes corresponds to the frequency of occurrence of terms, while the edges indicate co-occurrence relationships. Different colors represent clusters of related terms, reflecting thematic groupings in the research field. The arrows highlight key connections between clusters, emphasizing the role of biofilms, probiotics, and postbiotics in microbial interactions and antimicrobial strategies.

Result

Co-occurrence analysis

Co-occurrence analysis is a versatile method for exploring relationships between terms and identifying research trends across scientific fields. This study employed two complementary approaches to analyze different datasets, offering bibliometric and textual insights. The first analysis focused on creating a bibliographic map based on keyword co-occurrence data. Using VOSviewer, keywords appearing more than six times in the titles and abstracts of the selected publications were analyzed. From a total of 1,639 terms, 100 unique keywords were identified and grouped into four distinct clusters: i) gut microbiome, probiotics, and biofilm (red); ii) antimicrobial activity and postbiotic research (green); iii) antibiotic resistance and bacterial virulence (blue); and iv) lactic acid bacteria (LAB) and food microbiology (yellow) (Fig. 1A). This bibliographic analysis highlights major research themes and illustrates connections between keywords, offering a broad view of postbiotics, biofilm formation, and postbiotic applications in meat products. Notably, certain terms, such as "postbiotics" and "biofilm formation," appear across multiple clusters, reflecting their interdisciplinary relevance.

The second analysis focused on constructing a term co-occurrence map based on text data. This involved a detailed review of the titles and abstracts of 92 documents, yielding 3,779 terms. To refine the dataset, only terms that appeared at least 10 times were included. Applying this stricter threshold, 73 terms were extracted and organized into five distinct clusters (Fig. 1B): i) postbiotics and paraprobiotics: applications in meat products and gut health (red); ii) antibiotics and bacteriocins: mechanisms of action and role in infection control" (green); iii) biofilm formation and antimicrobial activities of LAB (blue); iv) MIC determination and antimicrobial efficacy assessments (yellow); and v) heat treatment and its effects on microbial behavior (purple). This text-based analysis provides a more detailed and granular view of research themes, particularly by identifying an additional cluster related to heat treatment.

The distinction between these analyses lies in their methodologies and outcomes. Based on bibliographic data, the first analysis provides a high-level overview of research themes and keyword relationships within the dataset. In contrast, the second analysis, grounded in textual data, employs stricter inclusion criteria, resulting in more specific and detailed clusters. These approaches complement one another, offering a comprehensive understanding of the research landscape surrounding postbiotics, biofilm formation, and meat product applications.

Bibliographic coupling: countries and sources

The bibliographic coupling analysis was performed using VOSviewer, applying thresholds to include only countries with a minimum of one document and at least five citations per country. Out of an initial pool of 35 countries, 31 met these criteria. Among them, India produced the highest number of documents related to postbiotics, biofilm, and meat products, with a total of 17 publications, accumulating 294 citations. In contrast, Iran, with just 14 documents, achieved a significantly higher citation count of 530 (Fig. 2A).

For sources, the analysis was conducted using VOSviewer, with thresholds set to include sources with a minimum of three documents and at least five citations per source. Out of an initial pool of 62 sources, 37 met these criteria (Fig. 2B). Among them, the journal *Probiotics and Antimicrobial Proteins* published seven documents, receiving a total of 104 citations. In comparison, *LWT* published four documents but garnered a higher citation count of 151. This integrative bibliometric analysis underscores the growing significance of postbiotics and biofilm research in meat product safety and quality, offering a nuanced understanding of global research distribution, collaboration patterns, and thematic evolution.

Postbiotics: definition and mechanisms

Postbiotics are biologically active compounds (Table 1) derived from non-viable microbial cells, their metabolites, or structural components, which confer functional benefits to food systems and human health (Rafique et al., 2023). Unlike probiotics, which must remain viable to deliver their health benefits, postbiotics are non-living bioactive compounds (Zhao et al., 2024). This stability and safety renders postbiotics particularly advantageous for applications in the meat industry, where product shelf life, microbial safety, and quality preservation are critical.

Short-chain fatty acids (SCFAs)

SCFAs, such as acetate, propionate, and butyrate, are microbial metabolites produced during the fermentation of carbohydrates (Deleu et al., 2021). In the meat industry, the ability of SCFAs to lower pH is pivotal for creating an inhibitory environment for spoilage microorganisms and foodborne pathogens. The reduction in pH destabilizes microbial cell membranes and disrupts enzyme activity, effectively enhancing the microbiological safety of meat products (Carneiro et al., 2024). The incorporation of SCFAs into preservation systems has also demonstrated extended shelf life and improved microbial stability, which are essential in maintaining product quality during storage and distribution.

Bacteriocins and antimicrobial peptides (AMPs)

Bacteriocins are ribosomally synthesized peptides with potent antimicrobial activity against food pathogens and include examples such as nisin and pediocin (Rahman et al., 2023). The LAB are particularly high-performing producers of these molecules. Bacteriocins function by inserting into bacterial membranes, forming pores that disrupt membrane integrity and lead to cell death. As natural preservatives, bacteriocins offer an alternative to synthetic additives, aligning with consumer preferences for clean-label products while ensuring food safety in fresh and processed meats (Bodie et al., 2024).

Exopolysaccharide (EPS)

EPS is a complex mixture of high-molecular-weight polysaccharides secreted by microbes and is known to play multifunctional roles in the meat industry (Kaur and Dey, 2023). Structurally, EPS contributes to the water-holding capacity (WHC) and texture of processed meats, improving product quality and sensory attributes. Functionally, certain EPS components exhibit antimicrobial activity by interfering with microbial adhesion and biofilm formation (Korcz and Varga, 2021). These properties address consumers' dual demands for natural ingredients and improve safety of meat products.

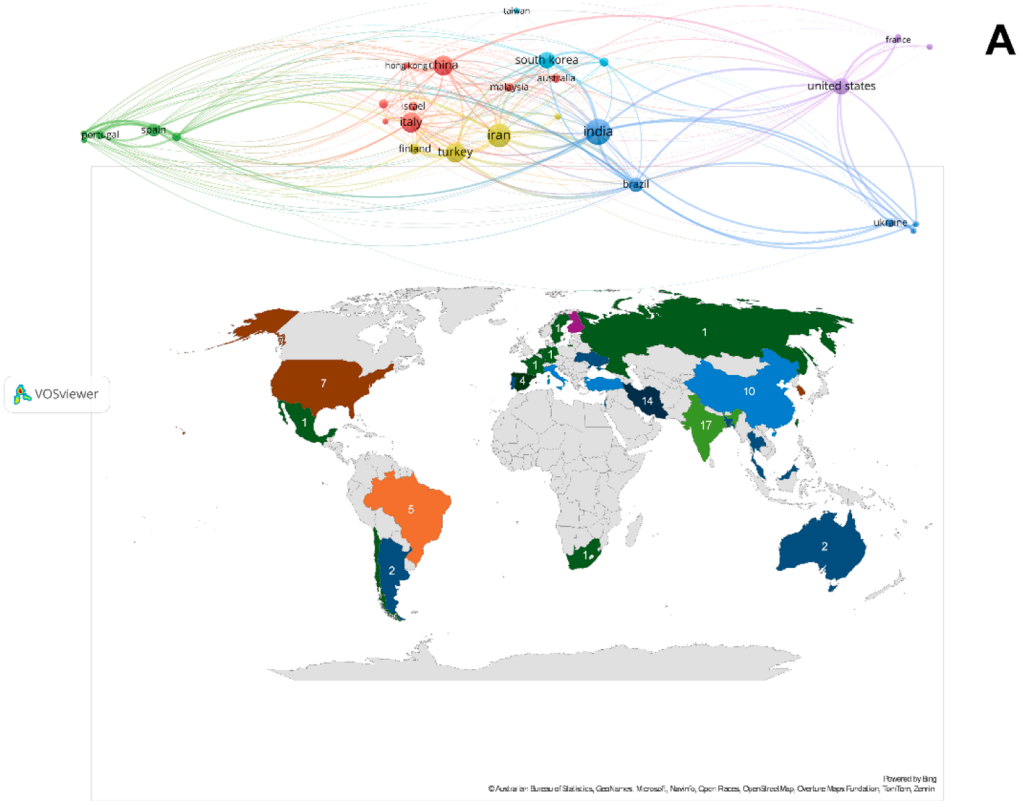
Enzymes and organic acids

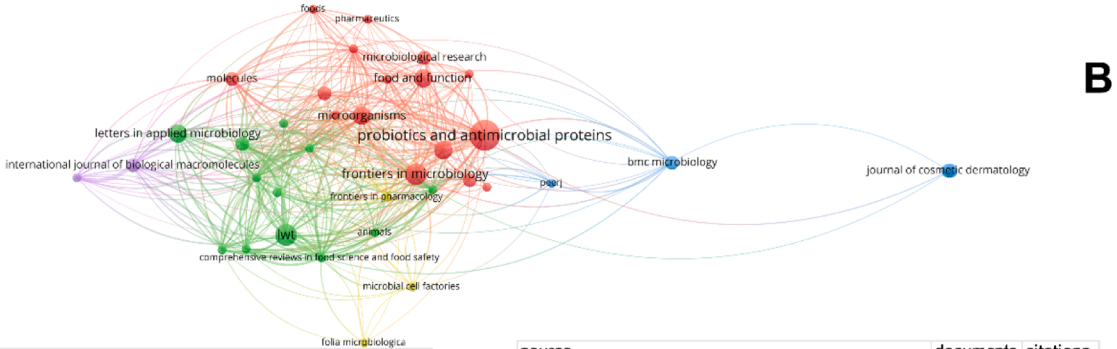
Enzymes, such as proteases derived from microbial activity, are widely used to enhance the tenderness and flavor profiles of meat products by breaking down proteins into smaller peptides and amino acids (Sun et al., 2020). Organic acids, including lactic acid and acetic acid, are extensively employed in meat surface decontamination protocols (Nkosi et al., 2021). These acids function as both bacteriostatic and bactericidal agents, reducing microbial loads on meat surfaces and thereby extending shelf life and minimizing spoilage.

Effects of postbiotics on meat quality

Postbiotics, comprising bioactive microbial metabolites such as organic acids, peptides, enzymes, bacteriocins, and antioxidants, have emerged as an advanced and sustainable approach to improving the quality and safety of meat (Table 2) (Rebezov et al., 2024). These

	Documents	Citations
	2	37
	2	52
	2	76
	5	307
	1	26
	10	47
	3	26
	1	18
	1	12
香港	1	19
	17	294
	14	530
	2	14
	10	69
	2	27
	1	26
	1	14
	2	30
	1	63
	1	18
	1	12
	7	143
	4	31
	1	11
	1	15
	2	30
	10	385
	2	13
	7	97





source	documents	citations
animals	1	10
archives of microbiology	1	18
biointerface research in applied chemistry	1	41
biomolecules	1	15
biotechnology repo	1	17
bmc microbiology	2	19
comprehensive reviews in food science and food safety	1	212
critical reviews in food science and nutrition	1	5
current microbiology	3	62
folia microbiologica	1	59
food and function	3	33
food microbiology	1	55
food production, processing and nutrition	1	11
food research international	2	105
foods	1	26
frontiers in cellular and infection microbiology	2	12
frontiers in microbiology	4	47
frontiers in pharmacology	1	11

source	documents	citations
frontiers in sustainable food systems	1	50
international journal of biological macromolecules	2	49
international journal of food microbiology	1	124
international journal of molecular sciences	2	5
italian journal of animal science	1	21
journal of cosmetic dermatology	2	21
letters in applied microbiology	3	14
lwt	4	151
microbes and infection	1	9
microbial cell factories	1	12
microbiological research	2	35
microorganisms	3	52
molecular oral microbiology	1	42
molecules	2	41
npj biofilms and microbiomes	1	19
pathogens	2	50
peerj	1	30
pharmaceutics	1	10
probiotics and antimicrobial proteins	7	104

Fig. 2. Global research impact and journal distribution in biofilm, probiotics, and postbiotics studies (A & B). (A) Country-wise network visualization and distribution of research contributions in biofilm, probiotics, and postbiotics studies. The map highlights the number of research documents contributed by different countries, with network connections representing international collaborations. The left panel presents the number of documents and citations for each country. (B) Network visualization of scientific journal distribution in the field of biofilm, probiotics, and postbiotics research. The colored clusters indicate co-citation relationships among journals, with key sources listed in the accompanying tables, displaying the number of published documents and their citations.

Table 1
Structural properties, mechanisms, and applications of postbiotics in the meat industry.

Postbiotic component	Example	Structure	Source bacteria	Mechanism of action	Applications in meat industry	References
Short-chain fatty acids	Acetate	CH_3COOH (Simple carboxylic acid with a methyl group)	*Lactobacillus acidophilus, Bifidobacterium breve*	Disrupt microbial membrane potential and acidify the environment, inhibiting pathogens.	Enhance microbial stability, inhibit spoilage bacteria like *Pseudomonas* spp. and *Listeria monocytogenes*, extend shelf life.	(Ahmed et al., 2015; Fang et al., 2024; Isaac-Bamgboye et al., 2024)
	Propionate	CH_3CH_2COOH (Three-carbon carboxylic acid)	*Propionibacterium freudenreichii*	Penetrates bacterial cells, lowering intracellular pH and disrupting metabolism.	Reduces spoilage by inhibiting *L. monocytogenes* and mold growth in processed meats.	(Isaac-Bamgboye et al., 2024; Lee et al., 2010)
	Butyrate	$CH_3(CH_2)_2COOH$ (Four-carbon carboxylic acid)	*Clostridium* sp.	Induces metabolic stress in pathogens by disrupting membrane integrity.	Improves preservation of fermented and cured meats, enhances flavor.	(Bui et al., 2015; Isaac-Bamgboye et al., 2024; Lan et al., 2020; Maiuolo et al., 2024)
Bacteriocins and antimicrobial peptides	Nisin	Polypeptide with a thioether ring structure and lanthionine residues	*Lactococcus lactis*	Bind to bacterial membranes, forming pores that lead to leakage of essential ions.	Control *L. monocytogenes, Clostridium botulinum*, and *Bacillus cereus* in ready-to-eat meats.	(Additives et al., 2017; Wu et al., 2023)
	Pediocin	Peptide with α-helical and hydrophobic regions	*Pediococcus acidilactici*	Disrupts membrane integrity, causing cell lysis in Gram-positive bacteria.	Preserves sausages and fermented meat products by inhibiting spoilage organisms.	(Nieto-Lozano et al., 2010)
	Plantaricin	Two-component peptide with helical structures	*Lactobacillus plantarum*	Interferes with cell membrane function in Gram-positive pathogens.	Extends shelf life of minimally processed meat products by reducing spoilage and pathogenic bacteria.	(Barbosa et al., 2016; da Costa, Voloski et al., 2019; Gong, Meng, and Wang, 2010)
	Enterocin	Peptide with disulfide bonds	*Enterococcus faecium*	Targets bacterial membranes, disrupting ion gradients and causing cytotoxicity.	Controls pathogens in vacuum-packed meats, enhances safety in cured meats.	(da Costa et al., 2019; Hugas et al., 2003)
Exopolysaccharide	Dextran	$(C_6H_{10}O_5)$n (Polysaccharide with α−1,6-glycosidic linkages and α−1,3 branches)	*Leuconostoc mesenteroides*	Forms a protective matrix that enhances texture and moisture retention.	Improves stability, texture, and juiciness in processed meat products like sausages.	(Korcz and Varga, 2021)
	Levan	$(C_6H_{10}O_5)_n$ (Fructan with β−2,6-glycosidic linkages)	*Bacillus subtilis*	Enhances water-holding capacity and prevents syneresis in processed foods.	Used as a stabilizer in emulsified meats, enhances mouthfeel in low-fat meat products.	(Korcz and Varga, 2021)
	β-glucan	$(C_6H_{10}O_5)_n$ (Glucose polymer with β−1,3/β−1,4 linkages)	*Lactobacillus delbrueckii*	Binds water and improves structural integrity of processed meats.	Increases shelf life and improves sensory qualities in meatballs, sausages, and burger patties.	(Korcz and Varga, 2021)
	Pullulan	$(C_6H_{10}O_5)_n$ (Glucan with α−1,4 and α−1,6 linkages)	*Aureobasidium pullulans*	Acts as an edible film, improving packaging and reducing oxidation.	Used in edible coatings for fresh and processed meats to prevent spoilage.	(Rashid et al., 2024)
Enzymes	Proteases	Polypeptides with catalytic triads (e.g., Ser-His-Asp)	*B. subtilis, L. plantarum*	Hydrolyze proteins into peptides and amino acids, enhancing tenderness and flavor.	Improve texture in fermented and processed meats like dry-cured hams and sausages.	(Song et al., 2023)
	Lipases	Hydrolase with catalytic domain for ester bond cleavage	*Candida rugosa, Pseudomonas fluorescens*	Degrade lipids, releasing fatty acids that enhance flavor and aroma.	Enhance flavor development in fermented sausages and dry-aged meats.	(Yao et al., 2021)
	Amylases	Enzymes with α-helical domains for starch hydrolysis	*Bacillus amyloliquefaciens*	Break down glycogen in meats, improving sweetness and texture.	Enhance sensory attributes in restructured and processed meat products.	(Abril et al., 2023; El-Leithy et al., 1973; The Amylase Research Society Of, J, 1988)
Organic acids	Lactic acid	$CH_3CH(OH)COOH$ (Hydroxycarboxylic acid with one hydroxyl group)	*Lactobacillus* spp.	Reduce pH, inhibiting growth of spoilage and pathogenic microorganisms.	Enhance microbial stability, flavor, and shelf life of fermented and marinated meats.	(Yi Wang et al., 2022)
	Acetic acid	CH_3COOH (Simple carboxylic acid)	*Acetobacter aceti*	Acidifies meat surfaces, preventing growth of spoilage organisms.	Controls spoilage bacteria in fresh and processed meats, especially vacuum-packed products.	(Yassunaka Hata et al., 2023)
	Propionic acid	CH_3CH_2COOH (Three-carbon carboxylic acid)	*Propionibacterium* sp.	Inhibits mold and yeast growth through acidification and metabolic disruption.	Used as a preservative in cooked and cured meats, extends shelf life.	(Piwowarek et al., 2018)
	Citric acid	$C_6H_8O_7$ (Tricarboxylic acid with three carboxylic groups and one hydroxyl group)	*Aspergillus niger*	Acts as a chelating agent, enhancing antioxidant effects and reducing spoilage.	Improves oxidative stability and prevents discoloration in fresh and processed meats.	(Behera et al., 2021; Książek, 2024)

Table 2
Uses of different postbiotics in meat products.

Meat product	Postbiotic component	Source microorganism	Applications in meat	Key outcomes	Critical insights	References
Dry-fermented sausage	Bacteriocins (e.g., nisin)	*Lactococcus lactis*	Used as natural preservatives in dry sausages.	Inhibition of *Listeria monocytogenes* and other pathogens; extended shelf life; sensory quality improvement.	Bacteriocin-targeted mechanism against pathogens makes them effective, but resistance development must be monitored over time.	(Korcz and Varga, 2021; Manassi et al., 2022)
Low-fat fermented sausage	Exopolysaccharide (EPS)	*Lactobacillus plantarum*	Incorporated to enhance texture and stability.	Improved rheological properties; reduced fat content without compromising sensory appeal.	EPS offers a clean-label alternative to synthetic texturizers, but batch-to-batch variability in EPS production can pose challenges.	(Manassi et al., 2022)
Cured meat products	Organic acids (e.g., lactic acid)	*Latilactobacillus sakei* ST 153	Applied for microbial safety and acidification of meat surfaces.	Controlled spoilage organisms like *Listeria* spp.; ensured food safety during curing and storage.	Organic acids' dual role as antimicrobials and acidifiers is effective, but excessive application may alter sensory attributes.	
Chicken burgers	Heat-killed probiotics	*Lactobacillus acidophilus*	Functional additive in processed meat patties.	Enhanced antioxidant properties; improved safety and shelf life of meat products.	Heat-killed probiotics retain functionality without viability concerns; however, their dose optimization for effectiveness requires further study.	(Manassi et al., 2022)
Ready-to-eat meat	Short-chain fatty acids (SCFAs)	Various lactic acid bacteria (LAB) species	Used as antimicrobial dipping solutions.	Reduction of spoilage and pathogenic microorganisms; stabilization of pH during storage.	SCFAs are effective in microbial inhibition, but their strong acidic taste in certain products may limit consumer acceptance.	(Korcz and Varga, 2021; Urban et al., 2024)
Smoked meat	Lactate	*Carnobacterium* spp.	Applied as a natural flavor enhancer and preservative.	Improved sensory properties; reduced microbial contamination during storage.	Lactate's dual function as a flavor enhancer and preservative is well-accepted, but its application in high concentrations may mask natural meat flavors.	(Manassi et al., 2022)
Dry-fermented sausage	Peptides (antimicrobial peptides, AMPs)	*Enterococcus faecium*	Surface application to enhance preservation.	Reduced spoilage; antimicrobial effects against foodborne pathogens.	AMP effectiveness depends on their stability during processing; environmental conditions like pH and temperature can reduce efficacy.	(Urban et al., 2024)
Ground meat	Cell-free supernatants (CFSs)	*Lactobacillus salivarius*	Sprayed on raw or cooked meat.	Prevention of lipid oxidation; improvement of sensory properties and microbial safety.	CFSs provide a non-viable, easy-to-handle solution; however, scalability for industrial applications remains underexplored.	(Manassi et al., 2022; Urban et al., 2024)
Processed meat products	Postbiotic metabolites	Various LAB species	Incorporated to reduce spoilage and improve quality.	Enhanced antioxidant effects; prevention of lipid oxidation and microbial spoilage.	Postbiotic metabolites present significant potential but require rigorous validation for regulatory approval in diverse global markets.	(Sheikhi et al., 2025)
Functional sausages	Fructooligosaccharides + Postbiotics	*Lactobacillus paracasei* & *Lactobacillus rhamnosus*	Combined with probiotics for functional benefits.	Improved aroma and flavor profiles; positive effects on sensory and volatile stability during fermentation.	Synergistic combinations of postbiotics and prebiotics can enhance product functionality but may increase production costs.	(Korcz and Varga, 2021; Manassi et al., 2022; Urban et al., 2024)

bioactive compounds can influence the lipid stability, protein integrity, microbial control, and color retention of meat (Aggarwal et al., 2022). While both red meat (e.g., beef, lamb) and poultry meat (e.g., chicken, turkey) benefit from postbiotic treatments, their distinct biochemical compositions and structural characteristics result in distinctive outcomes (Jalali et al., 2024). Understanding the nuanced mechanisms of postbiotics is crucial for their strategic application in meat preservation and quality enhancement (Fig. 3).

Lipid stability and oxidation control

Lipid oxidation is a key factor that compromises the quality of both red and poultry meat; however, the nature and relative proportions of compounds formed by lipid oxidation depend on the characteristic lipid composition of the slaughtered animal, as well as on many other factors such as types of ingredients, presence and concentrations of pro- and antioxidants, processing methods, and storage conditions (Amaral et al., 2018). In red meat, oxidative degradation is primarily driven by the pro-oxidant activity of myoglobin, which generates reactive oxygen species (ROS) through heme-mediated pathways (Liu et al., 2022; Papuc et al., 2017). Postbiotics mitigate this by stabilizing the heme group in myoglobin, chelating iron ions, and neutralizing ROS (Kaushik et al., 2024; Skrypnik and Suliburska, 2018). These actions prevent lipid peroxidation and preserve the structural integrity of lipid membranes, ensuring flavor and quality retention.

In contrast to red meat, poultry meat is highly susceptible to oxidative degradation because it has a higher proportion of polyunsaturated fatty acids (PUFAs) with multiple double bonds (Cartoni Mancinelli et al., 2021). Postbiotics, particularly those containing organic acids and antioxidant peptides, protect PUFAs by scavenging ROS and chelating pro-oxidant metals like iron and copper (Li et al., 2024). Additionally, postbiotics strengthen the cellular membranes of poultry meat, reducing lipid leakage and maintaining structural stability (İncili et al., 2023; Mishra et al., 2024).

While postbiotics effectively prevent lipid oxidation in both meat types, their mechanisms are tailored to specific challenges: stabilizing myoglobin in red meat and protecting PUFAs in poultry meat (Mutegi and Patimakorn, 2020; Sharma et al., 2022; Vasilev et al., 2017). This

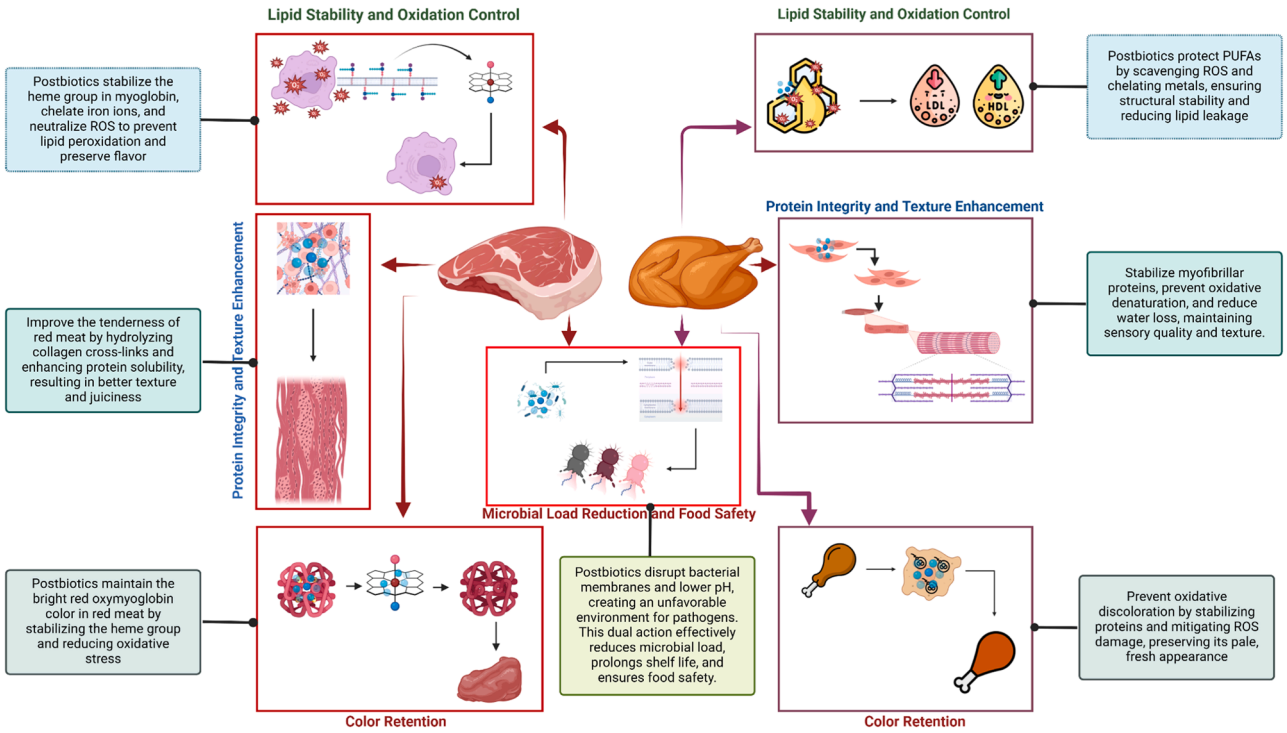


Fig. 3. Role of postbiotics in enhancing meat quality, stability, and safety. This schematic representation illustrates the multifunctional benefits of postbiotics in meat preservation and quality enhancement. Postbiotics contribute to (1) Lipid stability and oxidation Control by stabilizing the heme group in myoglobin and protecting polyunsaturated fatty acids (PUFAs) from oxidative damage, (2) Protein integrity and texture enhancement by hydrolyzing collagen cross-links and stabilizing myofibrillar proteins to improve tenderness and sensory attributes, (3) Microbial load reduction and food safety by disrupting bacterial membranes and lowering pH, thus inhibiting pathogen growth, (4) Color retention by maintaining oxymyoglobin stability and reducing oxidative stress, thereby preserving the fresh appearance of red and poultry meat. These mechanisms collectively enhance shelf life, food safety, and overall consumer acceptability.

adaptability underscores their molecular precision and relevance in addressing lipid oxidation unique to each meat type.

Protein integrity and texture enhancement

Protein integrity determines the texture, tenderness, and WHC of meat (Wang et al., 2023). Postbiotics influence these attributes by modulating protein structures and enzymatic interactions. In red meat, which contains dense myofibrillar proteins and abundant collagen, postbiotics address toughness by promoting controlled proteolysis (Wongphan et al., 2024). Proteolytic enzymes, such as subtilisin, hydrolyze collagen cross-links and partially denature myofibrillar proteins, improving tenderness and juiciness (Lantto et al., 2009; Nielsen, 2009). In addition, postbiotic-induced acidification enhances protein solubility, further contributing to improved texture (van Oort, 2009).

Compared to red meat, the muscle fibers of poultry meat are more delicate and contain less collagen (Ismail and Joo, 2017). Postbiotics stabilize myofibrillar proteins, preventing oxidative denaturation and improving WHC (İncili et al., 2023). This stabilization reduces drip loss during storage and cooking, preserving juiciness and sensory quality. Postbiotics also enhance the emulsification properties of poultry proteins, improving the texture of processed products (Sharafi et al., 2024).

Postbiotic enzymatic activity is particularly impactful for red meat, breaking down collagen and enhancing tenderness in tougher cuts (Jalali et al., 2024). In poultry meat, postbiotics play a protective role, stabilizing protein structures and minimizing water loss, which is critical for maintaining the delicate texture and sensory appeal of poultry (Rad et al., 2021).

Microbial load reduction and food safety

The antimicrobial properties of postbiotics significantly enhance the safety and shelf life of both red and poultry meat, although the predominant pathogens differ between the two (Serter et al., 2024). Red meat is commonly contaminated by *E. coli, L. monocytogenes*, and *Clostridium perfringens* (Mills, 2012). Postbiotics, particularly bacteriocins like nisin and pediocin, target these pathogens by disrupting their membranes, causing intracellular leakage and cell death (Cheruvari and Kammara, 2025). Organic acids in postbiotics further inhibit bacterial growth by lowering the pH and creating an unfavorable environment for pathogen survival (Peluzio et al., 2021).

Poultry meat, which is highly susceptible to contamination by *Salmonella* spp. and *Campylobacter jejuni*, benefits from the dual action of postbiotics (Chowdhury et al., 2023). In addition to reducing pathogen viability, postbiotics inhibit spoilage-associated enzymes secreted by bacteria, such as proteases and lipases, which accelerate meat degradation (Krishnamoorthy et al., 2023). This dual mechanism ensures prolonged microbial safety and extends the shelf life of poultry products.

The antimicrobial effects of postbiotics are universal but meat-specific in their targets. Red meat benefits from targeted action against *E. coli* and *Listeria*, while poultry meat requires broader microbial inhibition due to its higher initial microbial load. Postbiotics' ability to adapt to the microbial ecology of each meat type makes them a versatile tool for ensuring meat safety (Liu et al., 2023; Vinderola et al., 2022).

Color retention

Color is a critical quality attribute for meat, influencing consumer perception and acceptance (de Araújo et al., 2022). In red meat, postbiotics play a vital role in maintaining the bright red color of oxymyoglobin, which is associated with freshness (Incili et al., 2021; Li et al., 2022). They achieve this by stabilizing the heme groups in myoglobin and reducing the formation of metmyoglobin, which gives

the meat a brown and undesirable appearance (Bekhit and Faustman, 2005; Sheikhi et al., 2025). Antioxidants in postbiotics neutralize oxidative stress, preserving the natural red hue during storage (Hosseinzadeh et al., 2024).

In poultry meat, the absence of myoglobin shifts the focus to preventing oxidative discoloration caused by lipid and protein oxidation (İncili et al., 2021). Postbiotics stabilize proteins and reduce ROS-induced damage, ensuring that poultry meat retains its pale, fresh appearance (İncili et al., 2022). The role of postbiotics in color retention in red and white meat is more crucial for red meat, where the stabilization of oxymyoglobin directly influences consumer perception. In poultry meat, postbiotics mitigate secondary oxidative damage, indirectly preserving its visual appeal.

Biofilms in the meat industry: formation mechanisms and molecular insights

Biofilms are structured microbial communities embedded in an EPS matrix, providing bacteria with protection against environmental stresses, including sanitization and disinfection methods (Akter et al., 2024; Rahman et al., 2025). In the meat industry, biofilm formation poses significant health and economic risks by contributing to persistent contamination, product spoilage, and foodborne outbreaks. Understanding the molecular mechanisms underlying biofilm formation is essential for developing effective mitigation strategies (Oliulla et al., 2024).

Initial adhesion of planktonic cells to surfaces

Biofilm formation begins with the reversible adhesion of planktonic bacterial cells to surfaces. In meat processing facilities, biofilm formation commonly occurs on stainless steel and silicone materials and conveyor belts (Oliulla et al., 2024). The initial attachment is driven by bacterial surface structures, including fimbriae, pili, and flagella, which facilitate interactions with surfaces through hydrophobic and electrostatic forces (Rahman et al., 2023). Adhesins, such as microbial surface components recognizing adhesive matrix molecules (MSCRAMMs), further strengthen this attachment by binding to organic residues or imperfections on the surface (Ghasemian et al., 2015). Surface roughness and nutrient availability in the processing environment also play a significant role in promoting bacterial adhesion (Mu et al., 2023). In meat-processing environments, rapid formation of protein- and fat-rich conditioning films from blood, muscle proteins, and fats significantly enhances bacterial adhesion and reduces detachment, making initial attachment more persistent compared with low-organic food contact surfaces (Giaouris et al., 2014). .

Maturation and EPS production

Once the bacterial cells establish a firm attachment, they proliferate and begin producing EPS, which forms the structural scaffold of the biofilm. The EPS matrix consists of polysaccharides, proteins, lipids, and extracellular DNA (eDNA), which collectively provide stability and protection to the bacterial community. Molecular regulators, such as bis-(3′−5′)-cyclic dimeric guanosine monophosphate (cyclic di-GMP), play a pivotal role in this stage by activating EPS biosynthesis and repressing motility. Additionally, quorum sensing (QS) systems enable bacteria to communicate and coordinate biofilm maturation, ensuring the production of EPS and other biofilm-associated factors (Kameswaran et al., 2024). For instance, the *las* and *rhl* QS systems coordinate the biofilm development of *Pseudomonas aeruginosa* (Elnegery et al., 2021). The biofilm structure during this phase becomes increasingly complex, with nutrient concentration gradients and microenvironments supporting the coexistence of diverse microbial populations (Stevanovic et al., 2022). This matrix not only stabilizes the biofilm but also acts as a barrier against cleaning agents and antimicrobial treatments, significantly complicating eradication efforts. In meat-processing facilities, the EPS matrix frequently incorporates residual meat proteins and fats, resulting in denser biofilm structures that reduce disinfectant penetration and increase tolerance to antimicrobial treatments on meat-contact surfaces (Carpentier and Cerf, 2011; Møretrø and Langsrud, 2017).

Detachment and dispersion of biofilm cells

In the final stage of biofilm formation, bacteria within the biofilm undergo regulated detachment and dispersion, enabling colonization of new surfaces. This process is often mediated by enzymatic degradation of the EPS matrix, with enzymes such as dispersin B and alginate lyase playing critical roles (Ramakrishnan et al., 2022). QS also regulates dispersal by signaling cells to downregulate EPS production and restore motility, allowing bacterial cells to escape the biofilm (Guilhen et al., 2017). Environmental factors, such as nutrient depletion and mechanical shear forces, further contribute to cell detachment (Krsmanovic et al., 2021). Routine meat-processing operations, including cutting, deboning, carcass washing, and high-pressure water spraying, generate substantial mechanical shear forces that actively promote biofilm dispersion, enabling detached cells to spread to adjacent equipment and meat-contact surfaces. Once dispersed, these cells can revert to the planktonic state, spreading contamination to other areas in the processing facility (Chua et al., 2014). This cycle of detachment and recolonization is a significant driver of persistent contamination and cross-contamination in meat production environments.

Persistent contamination of surfaces

Biofilm formation on surfaces such as stainless steel, silicone, and rubber materials in meat processing facilities is a persistent challenge (Oliulla et al., 2024). These surfaces provide ideal niches for bacterial colonization, especially in hard-to-clean areas like crevices, welds, and joints. Organic residues from meat products further promote bacterial adhesion and biofilm development by providing nutrients. Bacteria use surface-associated proteins, such as LapA in *Pseudomonas* spp., to establish robust attachments, diminishing the effectiveness of cleaning protocols (Boyd Chelsea et al., 2014). Repeated wet–dry cycles, cold-room conditions, and continuous re-deposition of protein- and fat-rich meat residues further stabilize surface-associated biofilms, allowing them to persist despite routine sanitation and serving as chronic sources of recontamination in meat-processing facilities (Carpentier and Cerf, 2011; Møretrø and Langsrud, 2017). The persistence of biofilms on these surfaces creates an ongoing source of contamination, undermining operational hygiene and food safety.

Resistance to cleaning and sanitizing agents

Biofilms exhibit remarkable resistance to conventional cleaning and sanitizing agents, largely due to their molecular adaptations. The EPS matrix acts as a physical and chemical barrier, preventing the penetration of disinfectants. Within the biofilm, bacteria express stress response genes and upregulate efflux pumps, such as the multidrug efflux pump AcrAB-TolC in *E. coli*, which actively expel antimicrobial agents (Sun et al., 2014). These physiological changes enhance bacterial survival under harsh conditions. Moreover, the heterogeneous nature of biofilms creates microenvironments where some cells remain dormant, making them less susceptible to antimicrobial action. The high organic load originating from blood, proteins, and fats can further neutralize or inactivate sanitizing agents before they reach biofilm-embedded cells, substantially reducing disinfectant efficacy and necessitating higher chemical concentrations or longer exposure times (Møretrø and Langsrud, 2017). This resistance necessitates higher concentrations of sanitizers, increasing operational costs and environmental impacts.

Contribution to spoilage and foodborne pathogens

Biofilms are reservoirs for spoilage microorganisms and pathogenic bacteria, such as *L. monocytogenes, Salmonella* spp., and *E. coli* (Akter et al., 2024). These bacteria survive and thrive within the biofilm, shielded from external stresses by the EPS matrix. Pathogens express virulence factors, such as *inlA* in *L. monocytogenes* and *hilA* in *Salmonella* spp., enhancing their ability to infect humans through contaminated meat products (Iglesias et al., 2017). Furthermore, the close proximity of cells within biofilms facilitates horizontal gene transfer, including the exchange of antibiotic resistance genes, compounding the challenge of controlling contamination (Michaelis and Grohmann, 2023). Metabolic activity within biofilms also contributes to spoilage, producing volatile compounds that degrade meat quality and reduce shelf life. These combined effects result in significant economic losses and public health risks associated with foodborne outbreaks (Oliulla et al., 2024).

Mechanistic insight into antibiofilm activity of postbiotics

Postbiotics, which include microbial metabolites, cell-wall fragments, and extracellular compounds, offer a highly targeted strategy for disrupting biofilm formation (Prajapati et al., 2023). Their unique ability to interfere with bacterial metabolic pathways, signaling mechanisms, and cellular integrity positions them as a valuable tool for biofilm control (Wang et al., 2023). Unlike conventional antimicrobials, postbiotics act at multiple molecular and cellular levels, critically impairing biofilm formation processes while minimizing the risk of resistance development. This discussion delves deeper into the critical mechanisms by which postbiotics disrupt biofilm formation, focusing on bacterial physiology, intracellular pathways, and regulatory networks (Fig. 4).

Critical disruption of initial adhesion mechanisms

Postbiotics disrupt these adhesion mechanisms at both structural and

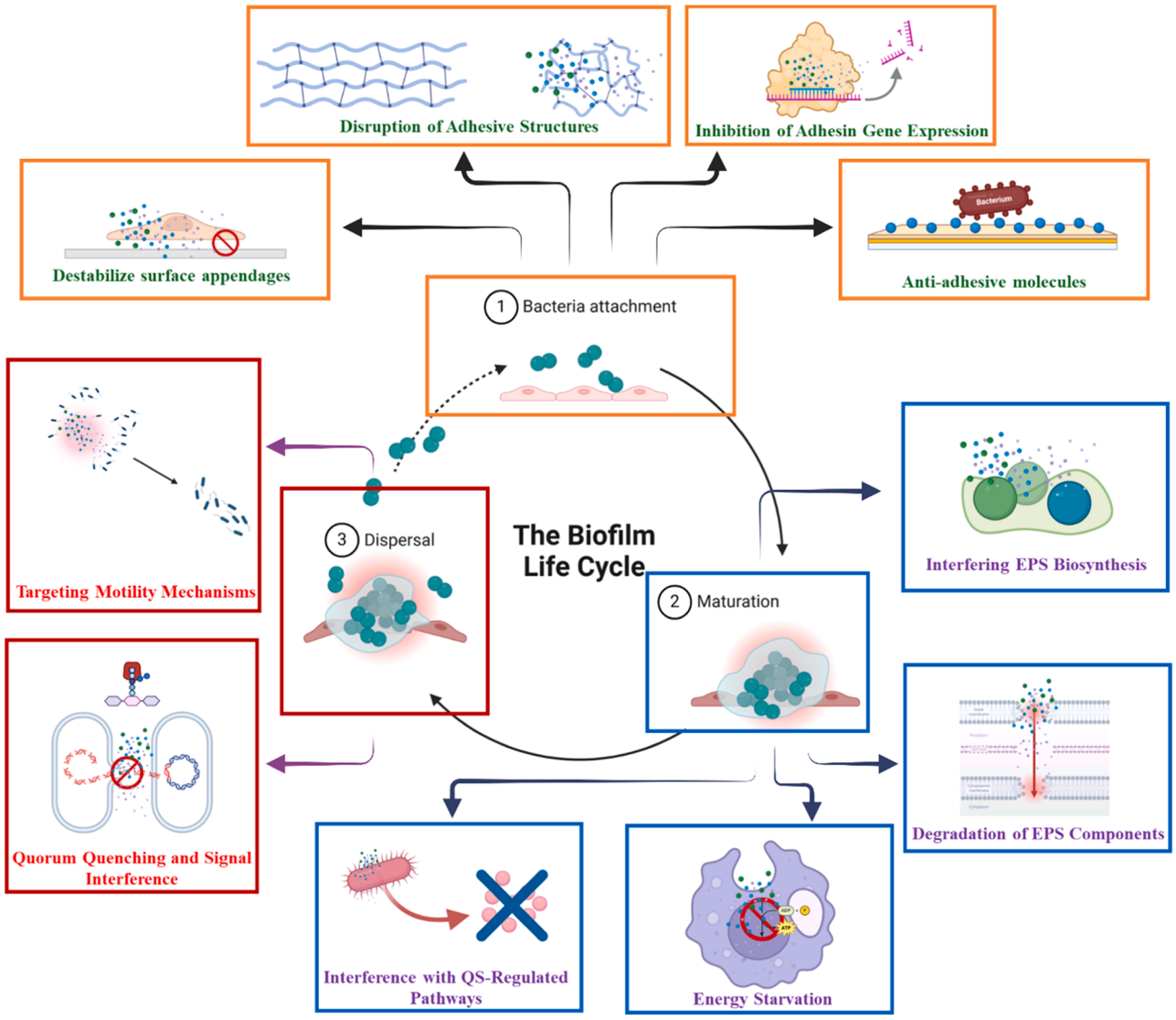


Fig. 4. Targeting the biofilm life cycle: strategies for biofilm inhibition and disruption. this schematic illustrates the biofilm life cycle, highlighting key stages— (1) Bacteria attachment, (2) Maturation, and (3) Dispersal—and various intervention strategies to inhibit or disrupt biofilm formation. Approaches to prevent bacterial attachment include destabilizing surface appendages, disrupting adhesive structures, inhibiting adhesin gene expression, and using anti-adhesive molecules (orange boxes). Strategies targeting biofilm maturation focus on interfering with EPS biosynthesis, degrading EPS components, interfering with quorum sensing (QS)-regulated pathways, and inducing energy starvation (blue boxes). Methods to promote biofilm dispersal involve targeting motility mechanisms and quorum quenching/signal interference (red boxes). These interventions collectively provide a multifaceted approach to biofilm control and eradication.

molecular levels (Jastrząb et al., 2021).

Disruption of adhesive structures

Postbiotic metabolites such as biosurfactants and organic acids destabilize surface appendages by altering bacterial cell wall integrity. Organic acids (e.g. lactic, acetic acids) produced by lactic acid bacteria (LAB) diffuse into pathogen cells in their undissociated form and dissociate intracellularly, acidifying the cytoplasm and collapsing proton motive force. This acidification leads to ATP depletion (from active proton expulsion) and can rupture cell membranes through osmotic imbalance (Ji et al., 2023). For example, biosurfactants reduce bacterial surface hydrophobicity, a key property required for effective adhesion (Wang et al., 2024). Additionally, cell-wall-penetrating postbiotics interfere with peptidoglycan crosslinking, weakening the structural framework that anchors adhesive proteins (Helmy et al., 2023).

Inhibition of adhesin gene expression

In addition to these direct physicochemical effects, postbiotics can influence the regulation of genes in pathogens that govern adhesion machinery. Exposure to certain postbiotic molecules triggers stress responses or signaling changes in pathogens that lead to reduced expression of adhesins, pili, or other attachment factors. For instance, sublethal doses of the bacteriocins nisin and bovicin not only altered surface hydrophobicity as noted above, but also downregulated the transcription of specific *Staphylococcus aureus* genes involved in adhesion and biofilm accumulation (such as *clfB, fnbA*, and *icaD*) (Mathur et al., 2018). Postbiotics downregulate the transcription of genes encoding adhesins and surface proteins (Zhao et al., 2024). For instance, they target *fimA* and *csgA*, which encode type 1 fimbriae and curli fibers, respectively, in *E. coli* (Azam and Khan, 2022). By suppressing these genes, postbiotics prevent bacteria from establishing strong, irreversible attachments to surfaces.

Surface-conditioning effects

Postbiotics coat surfaces with anti-adhesive molecules such as fatty acids or protein fragments, creating a hostile environment for bacterial adhesion (Nataraj et al., 2020). These coatings disrupt bacterial interactions with abiotic surfaces, such as stainless steel or silicone, commonly found in industrial and clinical environments (Hua et al., 2022; Isaac-Bamgboye et al., 2024). Probiotic-derived biosurfactants from *Lactiplantibacillus plantarum* or *Lactobacillus fermentum* have been shown to coat polystyrene or mucosal surfaces, preventing pathogen adhesion by making the surface less conducive to microbial attachment (Thakur et al., 2024).

Targeting maturation: EPS biosynthesis and cellular pathways

Biofilm maturation is driven by the secretion of EPS, which forms a protective matrix around bacterial cells. Postbiotics critically disrupt this phase by interfering with the biosynthesis of EPS components and regulatory pathways (Zhong et al., 2024). EPS production during biofilm maturation is governed by species-specific polysaccharide systems, including the *psl* and *pel* operons in *Pseudomonas aeruginosa* that encode structural polysaccharides (Colvin et al., 2012; Ghafoor et al., 2011), the icaADBC locus responsible for synthesis of polysaccharide intercellular adhesin (PIA/PNAG) in *Staphylococcus aureus* (Arciola et al., 2015; Fluckiger et al., 2005), and cellulose biosynthesis mediated by *bcsA* in *Escherichia coli* (Wikipedia, 2024).

Inhibition of cyclic di-GMP signaling

Cyclic di-GMP is a pivotal second messenger that regulates EPS production and biofilm maturation (Wang et al., 2023). Postbiotics such as organic acids and peptides inhibit the synthesis of cyclic di-GMP by targeting diguanylate cyclase's (DGCs) and phosphodiesterase's (PDEs), the enzymes that regulate its levels (Opoku-Temeng and Sintim, 2017; Whiteley and Lee, 2015). Reduced cyclic di-GMP concentrations impair the activation of the EPS biosynthesis operons, such as *psl, pel*, and *bcsA* (Castiblanco and Sundin, 2018; Pérez-Mendoza et al., 2015; Poulin and Kuperman, 2021).

Degradation of EPS components

Enzymatic postbiotics such as DNases, proteases, and glycosidases degrade key components of the EPS matrix (Ramakrishnan et al., 2022). For instance, DNases break down eDNA, a critical structural component of the matrix that facilitates cell to cell adhesion and horizontal gene transfer (Lander et al., 2024). Proteases target biofilm-associated proteins, such as Bap (biofilm-associated protein), which contribute to biofilm integrity (Peng et al., 2023). Enzymatic postbiotics (such as cell-wall-degrading enzymes from probiotics, e.g. lysozyme-like enzymes or DNases) are highly effective at breaking apart existing clumps by directly degrading the matrix or surface factors holding cells together. They can sometimes disperse established biofilms better than metabolic products can. However, enzymes tend to be specific (a β-glucanase will only target β-glucan-containing matrices, for example) and may not prevent initial aggregation if the target substrate hasn't accumulated yet. In contrast, biosurfactants and surface-active metabolites act earlier by preventing cell–cell attachment in the first place. Studies have found that even low concentrations of Lactobacillus-derived biosurfactant can inhibit aggregation of pathogens across a range of conditions, whereas comparable anti-aggregation effect by organic acids might require a sufficient concentration to maintain a low pH environment (Carvalho et al., 2022).

Energy starvation due to metabolic disruption

Postbiotics disrupt bacterial central metabolism, reducing the required energy source for EPS biosynthesis (Zhao et al., 2024). For example, lactic acid and acetate acidify the microenvironment, disrupting the proton motive force (PMF) and adenosine triphosphate (ATP) synthesis (Guan and Liu, 2020; Terradot et al., 2021). Furthermore, postbiotics inhibit glycolytic enzymes and tricarboxylic acid cycle (TCA cycle) intermediates, starving bacteria of the precursors required for EPS production (Fang et al., 2024; Hijová, 2024).

Interference with QS-regulated pathways

Postbiotics interfere with quorum sensing (QS)-regulated pathways that normally activate EPS biosynthesis and stress-protective responses. By degrading signaling molecules such as N-acyl homoserine lactones in Gram-negative bacteria and peptide autoinducers in Gram-positive bacteria, postbiotics suppress the transcription of QS-dependent antioxidant and EPS-protective genes (Piewngam et al., 2020). Enzymatic quorum-quenching postbiotics, including lactonases and acylases, further disrupt signal transmission by degrading AHL molecules or preventing receptor activation, thereby attenuating QS-mediated biofilm development genes (Paluch et al., 2020). In addition to enzymatic mechanisms, small-molecule postbiotics such as phenyllactic acid can competitively inhibit QS receptors, while lactic acid bacteria–derived short-chain fatty acids (SCFAs) indirectly impair QS signaling by destabilizing signal molecules and maintaining acidic microenvironments unfavorable for signal perception and activation. Through these combined mechanisms, postbiotics weaken QS-regulated EPS biosynthesis and impair biofilm maturation without directly relying on bactericidal activity (Che et al., 2024).

Mechanistic impact on detachment and dispersal

The final stage of biofilm development involves the detachment and dispersal of cells to colonize new surfaces. Postbiotics exert dual effects on this process by either enhancing premature detachment to destabilize biofilms or inhibiting dispersal mechanisms to contain bacterial spread.

Inhibiting motility-driven dispersal and reattachment

Dispersal and subsequent recolonization require motility structures,

such as flagella and type IV pili, which enable cells released from biofilms to migrate and reattach to new surfaces, thereby driving spatial spread and cross-contamination within processing environments (Pohlschroder and Esquivel, 2015). Postbiotics suppress the expression of motility genes like *fliC* (flagellin subunit) and *pilA* (pilus assembly protein), rendering bacteria immobile (Ghosh et al., 2004; Luna Rico et al., 2019; Nedeljković et al., 2021). Inhibition of motility also prevents the recolonization of detached cells on fresh surfaces (Alaei et al., 2023; Urban et al., 2024). Fatty acid postbiotics integrate into membranes and hinder flagellar rotation by disrupting membrane potential (Wang et al., 2024). By altering membrane potential, fatty acid postbiotics integrate into membranes and prevent flagellar rotation.

Induction of premature detachment

Certain postbiotics promote premature biofilm dispersal by enzymatically degrading the EPS matrix or disrupting cell−cell interactions (Che et al., 2024). However, dispersed cells are simultaneously exposed to antimicrobial postbiotic metabolites, such as ROS and AMPs, which eliminate them before they can form new biofilms (Cao et al., 2020). Under sub-inhibitory stress, LAB-secreted metabolites can cause population fragmentation by autoinducing dispersal (Leistikow Kyle et al., 2024).

Intracellular mechanisms and cellular physiology

Postbiotics exert profound effects on bacterial intracellular processes, targeting pathways critical for biofilm development and survival.

Disruption of membrane integrity

Postbiotic molecules, such as AMPs and fatty acids, destabilize bacterial membranes by integrating into the lipid bilayer (Rafique et al., 2023). This causes permeabilization of bacterial membranes, leakage of intracellular contents, and loss of membrane potential. Intracellular contents leak out as a result, and ion gradients that are necessary for biofilm maintenance are lost (Zhang et al., 2021). Lipid packing is further compromised by acidic environments, which can result in cell lysis or dormancy. Adhesion and structural maintenance are restricted by the loss of surface protein exposure (Ammendolia et al., 2021). The resulting cellular stress impairs energy production and biosynthetic pathways required for biofilm maintenance.

Induction of oxidative stress

Postbiotics induce oxidative stress in bacterial cells by promoting intracellular accumulation of reactive oxygen species (ROS), thereby overwhelming endogenous antioxidant defense systems such as catalase (*katA*), superoxide dismutase (*sodA*), and peroxidases. Excess ROS disrupt redox homeostasis and cause irreversible damage to cellular macromolecules, including membrane lipids, proteins, and nucleic acids, ultimately impairing bacterial viability and biofilm stability (Afzal et al., 2023; Alfei et al., 2024). Unlike quorum sensing interference, which primarily affects coordinated biofilm development, oxidative stress directly compromises bacterial survival and metabolic activity within established biofilms. Supporting evidence shows that microbial-derived metabolites modulate redox signaling pathways such as Nrf2–Keap1–ARE, thereby influencing the balance between oxidative stress and antioxidant capacity (Yang Wang et al., 2017). Moreover, *in vivo* models demonstrate that postbiotics enhance antioxidant gene expression and mitigate oxidative damage more effectively than probiotics, highlighting their potent role in disrupting redox regulation (Rezaie et al., 2024). This stress overwhelms bacterial antioxidant defenses, such as catalases and superoxide dismutase, reducing biofilm resilience (Prajapati et al., 2023).

Inhibition of protein synthesis

Postbiotic metabolites interfere with bacterial ribosomes, inhibiting protein translation (Mishra et al., 2024; Prajapati et al., 2023). For example, postbiotics are mainly composed of some small molecular bioactive substances which can bind to the ribosome and disrupt its function, impairing the production of biofilm-associated proteins, such as EPS enzymes and motility proteins (Zhao et al., 2024).

Energy metabolism disruption

Postbiotics deplete bacterial ATP reserves by disrupting key metabolic pathways (Bourebaba et al., 2022). Organic acids, for instance, inhibit the activity of ATP synthase by collapsing the PMF (Lu et al., 2011). Additionally, interference with glycolysis and the TCA cycle reduces the availability of energy and biosynthetic precursors, impairing biofilm growth and maintenance (Oliveira et al., 2023).

Modulation of stress response pathways

Biofilm-associated bacteria often rely on stress response pathways, such as the RpoS (sigma factor) and Cpx systems, to survive environmental insults (Akter et al., 2025). Postbiotics suppress these pathways, rendering bacteria more susceptible to external stresses, including cleaning agents and immune responses. Adaptive stress regulators are overpowered by acid shock caused by organic acids. Bacteriocins decrease tolerance to cleaning agents by interfering with signaling through envelope stress responses (Dawan and Ahn, 2022). Bacteria become less sensitive to changes in nutrients and oxidative fluctuations when they are exposed to several postbiotic stressors at once (Zhao et al., 2024).

Postbiotic applications in meat products: safety and preservation case studies

Antimicrobial efficacy against pathogens in meats

Postbiotics – the bioactive metabolites and compounds from probiotics – have shown potent antimicrobial effects when applied to meat and poultry products (Table 3). In experimental trials, cell-free supernatants and bacteriocins from lactic acid bacteria have significantly reduced major foodborne pathogens on meat surfaces. For example, a *Pediococcus acidilactici* postbiotic reduced *Listeria monocytogenes* by nearly 5 $\log_{10}$ in a broth within 6 hours when combined with a chelator (EDTA), and lowered *Salmonella* on chicken drumsticks by over 2 $\log_{10}$ immediately after dipping (İncili, Karatepe, Akgöl, Güngören, et al., 2022). Similarly, incorporating a *P. acidilactici* postbiotic (50–100% strength) into an edible chitosan coating on ready-to-eat frankfurters led to immediate pathogen reductions of ~1.6–3.2 $\log_{10}$ for *E. coli* O157:H7, *L. monocytogenes*, and *Salmonella* Typhimurium (relative to untreated controls) (İncili, Karatepe, Akgöl, Tekin, et al., 2022). Notably, these treatments did not adversely affect the product's pH, color, or sensory qualities highlighting their promise as clean-label antimicrobials (İncili, Karatepe, Akgöl, Tekin, et al., 2022).

A number of case studies demonstrate complete inhibition of pathogen growth during storage. A recent pilot-scale study on pork sausage found that coating with *Lactobacillus bulgaricus* postbiotic (300 mg/L) in 1% chitosan prevented any detectable *E. coli* O157:H7 or *Staphylococcus aureus* throughout 40 days of refrigeration (Sheikhi, Esfandiari, Rostamabadi, Noori, et al., 2025). In another approach, aerosolizing an *Lactiplantibacillus sakei* postbiotic onto fresh beef fillets achieved a ~3.3 $\log_{10}$ reduction of *L. monocytogenes* over 15 days at 4 °C (Valipour et al., 2024).

Inhibition of biofilm formation on surfaces

Beyond planktonic pathogens, postbiotics and bacteriocins can combat bacterial biofilms on meat surfaces and processing equipment – a critical aspect of food safety. Research has shown that certain LAB-derived bacteriocins are effective in disrupting established biofilms of *L. monocytogenes*. For example, lactocin AL705 (from *Latilactobacillus curvatus*) at 800 AU/mL effectively eradicated pre-formed *Listeria*

Table 3
Applications of postbiotics and related agents in meat products for food safety and preservation.

Postbiotic Type	Meat Product	Target Microorganisms	Mechanism of Action	Observed Effects	Application Format	Study/ Source
LAB postbiotic (CFS + lactic acid)	Chicken drumsticks	*Escherichia coli, Salmonella* spp., *Listeria monocytogenes*	Membrane damage, acidification	≥2 $\log_{10}$ reduction; shelf-life extended	Dipping treatment	(İncili et al., 2022)
Pediococcus acidilactici postbiotic + chitosan	Frankfurters	*E. coli* O157:H7, *Salmonella* spp., *L. monocytogenes*	Bacteriocin action + pH lowering	Immediate 1.6–3.2 $\log_{10}$ pathogen reduction	Edible coating	(İncili et al., 2022)
Lactobacillus bulgaricus postbiotic + chitosan	Sausages	*E. coli* O157:H7, *Staphylococcus aureus*	Cell envelope disruption; antimicrobial peptides	No detectable pathogens after 40 days	Surface coating	(Sheikhi et al., 2025)
Aerosolized *Lactiplantibacillus sakei* postbiotic	Beef fillets	*L. monocytogenes*	Acidification, cell viability loss	~3.3 $\log_{10}$ reduction at 4 °C over 15 days	Spray application	(Valipour et al., 2024)
Lactiplantibacillus plantarum / L. sakei postbiotics	Chicken breast	*Salmonella* spp., *L. monocytogenes*	Bacteriostatic via pH, membrane stress	Growth suppression; 9-day shelf-life extension	Dipping treatment	(Serter et al., 2024)
Lactocin AL705 (bacteriocin)	Stainless steel, Teflon (simulated meat contact)	*L. monocytogenes* (biofilms)	Biofilm degradation, membrane pore formation	~5.5 $\log_{10}$ biofilm removal	Surface treatment	(Melian et al., 2024)
Lactobacillus curvatus / L. plantarum CFS	In vitro on meat-contact surfaces	*L. monocytogenes*	Quorum sensing inhibition, motility reduction	Biofilm suppression; gene downregulation	Culture supernatant	(Hossain et al., 2021)
LAB-derived supernatant	Simulated meat surface (*in vitro*)	*Staphylococcus aureus*	Reduced adhesion, EPS inhibition, cell hydrophobicity ↓	Biofilm prevention	Cell-free filtrate	(Mao et al., 2023)
Bacteriocin (e.g., bifidin)	Ground meat	General spoilage flora	Cell leakage, metabolic disruption	3-month preservation at 4 °C	Direct incorporation	(Mokhtar et al., 2016)
Pediocin, nisin (commercial)	Ham, turkey, beef	*L. monocytogenes*, spoilage bacteria	Cell membrane pore formation	Shelf-life extension, spoilage delay	Edible films, packaging	(Bodie et al., 2024)

biofilms on stainless steel and Teflon, reducing viable cells by ~5.5 $\log_{10}$ within 3 days. Even under conditions simulating food-processing environments (10 °C, continuous flow), this bacteriocin caused substantial loss of biofilm biomass, thickness and surface coverage, as visualized by confocal microscopy (Melian et al., 2024).

Postbiotic metabolites can also *prevent* biofilms from forming in the first place. In vitro experiments with LAB supernatants have demonstrated inhibition of the early steps of biofilm development. For instance, cell-free supernatants from *L. curvatus* and *L. plantarum* strains significantly curtailed *L. monocytogenes* swimming motility and attachment, leading to reduced biofilm formation and even downregulation of the pathogen's biofilm, virulence, and quorum-sensing genes (Hossain et al., 2021). Likewise, a multi-strain LAB culture filtrate was shown to "considerably slow" the growth of *S. aureus* and prevent it from forming biofilms, impairing key biofilm traits such as cell-surface hydrophobicity, exopolysaccharide matrix (PIA) production, extracellular DNA, and motility (Mao et al., 2023). These modes of action, involving interfering with adhesion and matrix formation, are often attributed to biosurfactants and other signaling-disrupting molecules in the postbiotic mix. Indeed, probiotic-derived biosurfactants can coat surfaces and modulate wettability, thereby blocking pathogen attachment.

Shelf-life extension and quality preservation

A major benefit of applying postbiotics to meat is enhanced preservation as they extend shelf life by suppressing spoilage microbes and maintaining product quality. Some experimental studies documents reduced total microbial loads and delayed spoilage in postbiotic-treated meats. In a refrigerated chicken model, LAB postbiotic dips extended the microbiological shelf-life of raw chicken breast by 9 extra days compared to untreated meat (5 days vs. 14 days until spoilage levels reached) (Serter et al., 2024). This improvement approached the performance of a lactic acid dip (which gave 12 extra days) (Serter et al., 2024), demonstrating that postbiotics can meaningfully prolong freshness. Similarly, chicken drumsticks treated with 10% LAB postbiotic (plus 1% lactic acid) showed the lowest total aerobic plate counts during storage, without any adverse change in meat color (İncili et al., 2022).

Postbiotic coating has also been shown to protect the quality of processed meats during chilled storage. Coatings of chitosan enriched with *P. acidilactici* postbiotics on frankfurters not only controlled pathogens as noted, but also curtailed the growth of lactic acid spoilage bacteria and total viable flora over 35 days ($p < 0.05$) (İncili et al., 2022). In the sausage study with *L. bulgaricus* postbiotics, the highest postbiotic–chitosan treatment achieved the strongest inhibition of mesophilic and psychrophilic spoilage organisms, as well as molds and yeasts, throughout 40 days. Those sausages remained within acceptable ranges for pH, moisture, and volatile nitrogen, indicating no spoilage had occurred (Sheikhi et al., 2025). In fact, by the end of storage the postbiotic-treated sausages had zero detectable pathogenic bacteria (Sheikhi et al., 2025), underscoring both safety and extended shelf stability.

There are even reports of dramatic shelf-life extension under certain conditions. One study found that adding a purified *Bifidobacterium* bacteriocin ("bifidin") to ground meat enabled the meat to be stored for *up to 3 months at 4 °C* without spoilage (Mokhtar et al., 2016). While such an extended duration is exceptional, it illustrates the preservation potential of these bio-preservatives. More routinely, pediocin (from *Pediococcus*) and nisin (from *Lactococcus*) bacteriocins are known to retard spoilage in cured meats: for example, pediocin PA-1 can minimize growth of spoilage lactobacilli during meat storage and shows synergistic effect when combined with organic acid salts (Bodie et al., 2024). Overall, by suppressing both pathogenic and spoilage microbes, postbiotic treatments help intact the quality of meat products for longer, without the need for synthetic additives. This aligns with the food industry's pursuit of "clean label" preservatives that ensure safety and shelf-life while preserving organoleptic properties.

Synergistic combinations with packaging and hurdle technologies

A major advancement in postbiotic applications lies in their integration with active packaging and multi-hurdle technologies to enhance food safety. Postbiotics can be incorporated into biopolymer-based films or coatings (e.g., chitosan, alginate, polylactic acid), forming bioactive packaging systems with sustained-release antimicrobial functions (Ramazanidoroh et al., 2025). Such systems, when enriched with compounds like nisin, lactic acid, or bacteriocin-rich CFS, provide effective inhibition against pathogens such as Listeria monocytogenes, Salmonella enterica, and Brochothrix thermosphacta in various meat products

(Soleimani et al., 2024).

Furthermore, postbiotics display strong synergy when combined with hurdle technologies which can be defined as the strategic application of multiple preservation methods to ensure microbial safety without compromising food quality (Isaac-Bamgboye et al., 2024). Mild thermal treatments, high-pressure processing (HPP), pulsed electric fields (PEF), and vacuum packaging enhance the efficacy of postbiotics by compromising microbial cell defenses and improving diffusion into biofilms (Yang and Liao, 2024). In addition to antimicrobial effects, postbiotic-infused edible films contribute to moisture retention, oxidative stability, and even aroma modulation, further promoting shelf-life extension (Soleimani et al., 2024; V et al., 2022). Emerging innovations include intelligent packaging systems where embedded biosensors detect spoilage markers (e.g., pH, volatile amines) and trigger the controlled release of postbiotics (Cheng et al., 2022). This dynamic delivery model has the potential to revolutionize food packaging by offering responsive and targeted interventions.

*7.5. Safety aspects*Postbiotics are inherently safer than live probiotics for meat applications because they consist of non-viable microbial cells and or their bioactive components, eliminating risks associated with microbial survival, proliferation, and horizontal gene transfer in food matrices (Salminen et al., 2021). Key postbiotic constituents used in meat systems, including organic acids, short-chain fatty acids, bacteriocins such as nisin, and biosurfactants, have a well-documented history of safe use in foods when applied at appropriate concentrations (Thorakkattu et al., 2022). Their antimicrobial activity is mediated through non-specific physicochemical mechanisms, such as membrane disruption and pH modulation, which impose minimal selective pressure for antimicrobial resistance compared with antibiotic-based interventions (Moradi et al., 2020). Nevertheless, dose optimization, residue evaluation, and regulatory harmonization remain essential to ensure the safe large-scale application of postbiotics as clean-label biofilm control agents in meat-processing environments (Khani, Bonyadi, et al., 2025).

Challenges and future directions

Current limitations

Despite the promising potential of postbiotics in biofilm control and food safety, diverse challenges hinder their widespread industrial adoption.

Scalability and cost of postbiotic production

The economic feasibility of postbiotic production remains a major hurdle, as large-scale fermentation requires precise control over microbial growth conditions, extraction, and purification. The cost-intensive nature of these processes limits industrial scalability (Isaac-Bamgboye et al., 2024). The development of cost-effective production methods through metabolic engineering and alternative substrates, such as agro-industrial byproducts, has been suggested to enhance yield and economic viability (Aamer Mehmood et al., 2021).

Stability and activity retention in industrial settings

The efficacy of postbiotics is highly influenced by processing conditions, including temperature, pH, and interactions with components of food matrices (Gurunathan et al., 2024). Studies indicate that encapsulation techniques, such as microencapsulation and nano-delivery systems, improve postbiotic stability and bioactivity retention during food processing and storage (Alu'datt et al., 2022). However, further research is needed to optimize encapsulation efficiency and ensure controlled release under industrial conditions.

Lack of standardized protocols for postbiotic application

The absence of universal guidelines for postbiotic use in food processing hampers regulatory approval and industry adoption. Variability in postbiotic composition, concentration, and application methods leads to inconsistent efficacy in biofilm control (da Silva Vale et al., 2023). Although some postbiotic ingredients have achieved GRAS status in the U.S. like Cargill's EpiCor (2021) and Ildong Bioscience Co (2024), Ildong Bioscience's BBR4401® (2024), Cargill Health (2021). There is currently no dedicated regulatory category or framework for postbiotics. Instead, regulatory bodies classify them under existing categories (food, dietary supplements, pharmaceuticals) based on use (Salminen et al., 2021; Vinderola et al., 2025). In Japan, postbiotic ingredients may be approved under the Food with Function Claim system; in Europe, they must comply with conventional food or supplement regulations; and in Australia, select inactivated microbial ingredients are accepted as listable medicines (Guglielmetti et al., 2025; Salminen et al., 2021). A recent decision tree model proposes classifying postbiotics into fragmented cell, intact-cell, complex preparation, or metabolic product subcategories, offering a structured basis for harmonizing safety assessments and regulatory standards (Guglielmetti et al., 2025).

Future research needs

To fully harness the potential of postbiotics in biofilm prevention and food safety, targeted research efforts are essential (Fig. 5).

High-throughput screening for novel postbiotic candidates

Advancements in metagenomics and synthetic biology have enabled the discovery of novel postbiotic compounds with enhanced antimicrobial and biofilm-inhibitory properties (Cerioli et al., 2024). High-throughput screening techniques, such as clustered regularly interspaced short palindromic repeat (CRISPR)-based functional assays and metabolomic profiling, can facilitate the identification of potent bioactive metabolites (Ayon, 2023). Further research is required to elucidate the molecular mechanisms underlying postbiotic activity and their interactions with microbial communities.

Integration with advanced technologies

The incorporation of postbiotics with emerging technologies, such as nanotechnology and microfluidic systems, offers new possibilities for targeted biofilm control. Nanocarrier-based postbiotic delivery has shown promising results in enhancing antimicrobial efficacy while minimizing adverse effects on food quality (Rezagholizade-shirvan et al., 2024). Future studies should focus on optimizing nanoparticle formulations, ensuring controlled release mechanisms, and assessing their safety in food applications.

Long-term impact studies on biofilm control and microbial resistance

While postbiotics have demonstrated significant antimicrobial and antibiofilm properties, their long-term effects on microbial ecology, resistance evolution, and cross-resistance potential remain underexplored. Comprehensive longitudinal studies using omics technologies, such as transcriptomics and proteomics, can provide insights into bacterial adaptation and resistance mechanisms (Li and Wen, 2021). Additionally, *in situ* industrial trials are essential to evaluate the real-world efficacy of postbiotics and their impact on microbial community dynamics in food processing environments.

Conclusion

Biofilm-associated contamination in meat processing remains a critical food safety challenge, driven by microbial resilience and ineffective conventional interventions. With their ability to disrupt key biofilm-forming mechanisms while enhancing meat quality attributes, postbiotics present a compelling alternative to synthetic preservatives. This review highlights their multifaceted bioactivity, spanning antimicrobial action, metabolic disruption, and oxidative stabilization, underscoring their potential as an industry-transformative solution. However, limitations in production scalability, standardization, and

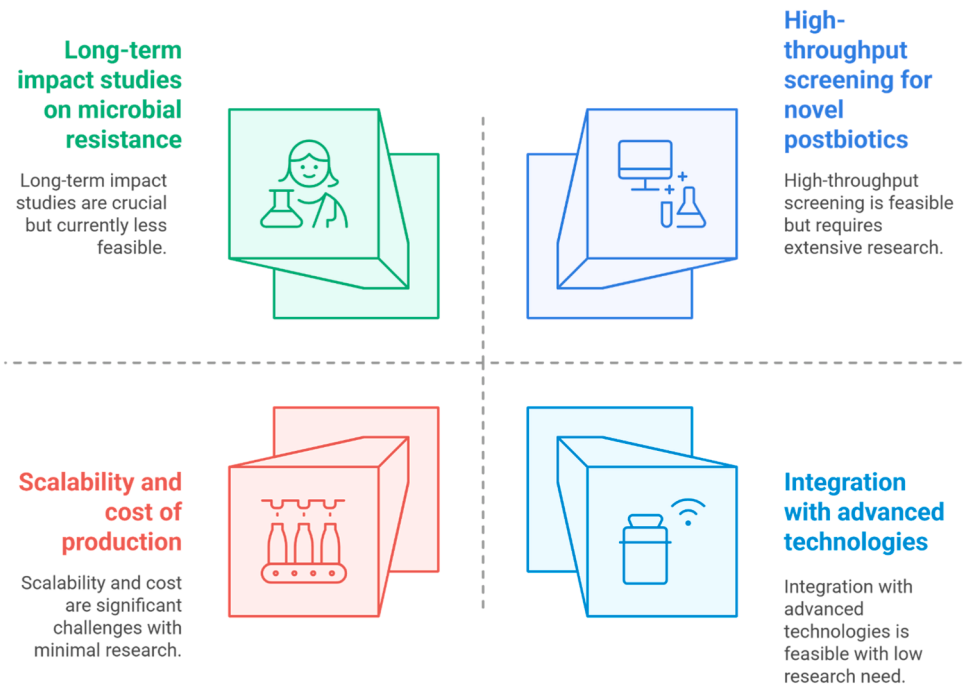


Fig. 5. Challenges and future directions in postbiotic application.

regulatory approval necessitate further research. Advancing postbiotic applications requires a multidisciplinary approach integrating omics-driven compound discovery, metabolic engineering, and controlled delivery technologies. Long-term studies on microbial adaptation and industrial feasibility are also essential for their widespread adoption. By bridging microbiological innovation with applied food safety strategies, postbiotics offer a sustainable and mechanistically robust approach to mitigating biofilm risks, ensuring safer and higher-quality meat products in an era of increasing regulatory and consumer scrutiny.

Data availability

All the data are in the manuscript.

CRediT authorship contribution statement

Shirin Akter: Writing – original draft, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization. **Md. Ashikur Rahman:** Writing – original draft, Visualization, Software, Data curation, Conceptualization. **Md. Ashrafudoulla:** Writing – review & editing, Visualization, Supervision, Investigation. **A.G.M. Sofi Uddin Mahamud:** Writing – original draft, Visualization. **Chowdhury Sanat Anjum Reem:** Writing – original draft. **Md Anamul Hasan Chowdhury:** Writing – original draft. **Meidistria Tandi Rapak:** Writing – original draft, Visualization. **Hye-Jeong Yoon:** Writing – review & editing, Supervision. **Sang-Do Ha:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Disclosures

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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