



Next-Generation Prebiotics: Exploring Galacto-Oligosaccharides for Precision Microbiome Modulation and Functional Food Innovation

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Abstract: Galacto-oligosaccharides (GOS) are nondigestible or partially digestible carbohydrates that have attracted considerable attention for their ability to selectively support beneficial intestinal microorganisms and their potential applications in functional foods. They occur naturally in human milk and certain plant-derived foods and are commercially produced primarily through enzymatic transgalactosylation of lactose using β -galactosidase. GOS composition, degree of polymerization, and glycosidic linkages influence its fermentation characteristics, microbial selectivity, and technological functionality. Their principal prebiotic mechanism involves microbial utilization in the intestine, which changes microbial composition and increases metabolite production, particularly short-chain fatty acids, that support intestinal and systemic physiological processes. Research has examined GOS in relation to bowel function, mineral absorption, immune responses, metabolic health, and infant nutrition product development. However, the magnitude and consistency of these effects depend on the GOS preparation, dosage, duration of consumption, background diet, and characteristics of the individual microbiome. Excessive intake may cause gastrointestinal discomfort, including bloating and flatulence. Recent advances in enzyme engineering, bioreactor design, analytical characterization, and valorizing dairy by-products have expanded opportunities for sustainable GOS production. This review critically examines GOS chemistry, production, mechanisms of action, potential health effects, safety considerations, and food applications. It also identifies research priorities, including structure–function relationships, personalized prebiotic interventions, long-term clinical evaluation, and the development of cost-effective production technologies. Stronger integration of mechanistic, clinical, and food-processing research will be essential to translate GOS science into evidence-based functional food innovations. **Keywords-** Customer Satisfaction, Quick Service Restaurant, KFC, Food Quality, Service Speed, QSR Marketing, Consumer Behaviour.

Keywords: Galacto-oligosaccharides; GOS; prebiotics; β -galactosidase; gut microbiota; bifidobacteria; short-chain fatty acids; functional foods; dairy technology; human nutrition.



I. INTRODUCTION

Growing interest in functional foods has driven research into dietary components that provide physiological benefits beyond their conventional nutritional contributions. Among these components, prebiotics have gained importance because they can influence the intestinal microbiota and its interactions with the host. Galacto-oligosaccharides (GOS) are particularly relevant because, at appropriate concentrations, they can be incorporated into foods without substantially altering their overall nutritional character.

GOS are a heterogeneous group of carbohydrates containing galactose residues linked through different glycosidic bonds. Commercial GOS preparations generally contain mixtures of oligosaccharides with different chain lengths and linkage patterns, together with variable quantities of residual lactose, glucose, and galactose. These differences matter because GOS's physiological properties depend not only on total concentration; molecular structure and individual microorganisms' ability to use specific structures also influence biological activity.

The contemporary definition of a prebiotic emphasizes a substrate that host microorganisms selectively utilize and that confers a health benefit. This definition highlights the importance of demonstrating both microbiota-mediated utilization and a relevant benefit rather than assuming that every fermentable carbohydrate is automatically a prebiotic (Gibson et al., 2017).

GOS have become important ingredients in infant formula, dairy products, nutritional formulations, and other functional food systems. Research on intestinal microbial ecology supports their application, particularly by enriching certain bifidobacteria and producing fermentation metabolites. Nevertheless, prebiotic effects vary between individuals, and evidence supporting one physiological outcome should not be generalized to every GOS preparation or consumer.

Recent literature has examined GOS biosynthesis, molecular structure, interactions with microorganisms, biological activities, and industrial applications. In particular, 2025 reviews have emphasized structure–function relationships and advances in enzymatic production, indicating that this is an active, rapidly developing research area. This review integrates these themes with a critical discussion of clinical evidence, dairy-industry opportunities, technological constraints, and future research needs.



II. BIOSYNTHESIS AND INDUSTRIAL PRODUCTION OF GOS

Enzymatic synthesis

The principal commercial method for producing β -GOS is the enzymatic conversion of lactose using β -galactosidase. This enzyme can catalyze both lactose hydrolysis and transgalactosylation. During hydrolysis, β -galactosidase breaks down lactose into glucose and galactose. During transgalactosylation, the enzyme transfers a galactosyl group to an appropriate acceptor molecule, forming new glycosidic bonds and generating oligosaccharides. The relative contributions of these reactions determine the final product composition. Because hydrolysis and transgalactosylation occur simultaneously, GOS accumulation depends on the balance between synthesis and subsequent degradation.

Factors affecting GOS yield

The principal variables influencing GOS production include:

- **Lactose concentration:** High substrate concentrations can favor transgalactosylation relative to hydrolysis, although the optimum depends on the enzyme and process configuration.
- **Enzyme source:** β -Galactosidases from different microorganisms exhibit distinct catalytic properties and product profiles.
- **Temperature and pH:** These affect enzyme activity, stability, reaction kinetics, and the distribution of individual oligosaccharides.
- **Reaction time:** Prolonged reactions may increase initial GOS formation but can also promote their subsequent hydrolysis.
- **Water activity and reaction medium:** These variables influence substrate availability and the balance between hydrolysis and transfer reactions.
- **Product inhibition and substrate composition:** Accumulating sugars can alter reaction rates and final composition.

Accordingly, optimization should consider not only maximum total GOS yield but also the desired oligosaccharide profile, enzyme productivity, purification requirements, and energy consumption.



Microbial sources of β -galactosidase

Researchers have investigated β -galactosidases from microorganisms such as *Aspergillus* and *Bacillus* species for GOS production. Enzyme selection depends on temperature tolerance, pH stability, transgalactosylation activity, substrate specificity, and suitability for food manufacturing. Enzymes with high transgalactosylation activity can improve oligosaccharide yield. However, enzyme performance under laboratory conditions may differ from performance in concentrated industrial lactose solutions. Industrial selection must therefore consider productivity, operational stability, food-grade status, and process economics.

Dairy by-products as substrates

Whey and lactose-rich dairy streams are promising feedstocks for GOS production. Whey generated during cheese manufacture contains lactose and can be a valuable resource when processed appropriately. Converting lactose-rich streams into higher-value oligosaccharide ingredients may improve resource efficiency and reduce the environmental burden associated with underutilized dairy by-products.

However, direct use of whey requires consideration of protein content, mineral composition, microbial quality, and the possible need for pretreatment. Purification and concentration can also substantially increase production costs.

Costa et al. (2025), in their systematic review and meta-analysis of GOS biosynthesis, examined transgalactosylation processes and highlighted the potential of dairy-derived substrates. This approach is particularly relevant to integrated dairy biorefineries, where lactose recovery, enzyme utilization, and product separation can be optimized together.

Immobilized enzymes and process intensification

Immobilizing β -galactosidase on suitable carriers may facilitate enzyme recovery and reuse, improve process control, and enable continuous production. Nevertheless, immobilization does not guarantee increased GOS yield. Mass-transfer limitations, changes in enzyme conformation, carrier cost, and enzyme leakage may affect performance.



Future process development should compare free and immobilized enzymes using standardized measures such as GOS yield, space–time productivity, enzyme half-life, energy use, and cost per kilogram of purified product.

III.MECHANISMS OF PREBIOTIC ACTION

Resistance to host digestion

A major characteristic of dietary GOS is that a substantial fraction can escape digestion in the upper gastrointestinal tract and reach the large intestine. The extent of digestion depends on molecular structure and the specific preparation.

Once in the colon, GOS can serve as a fermentable substrate for microorganisms with the necessary transport systems and carbohydrate-degrading enzymes. This underpins their prebiotic activity.

Selective utilization by intestinal microorganisms

GOS are frequently associated with increased bifidobacterial abundance or activity. Some lactobacilli and other intestinal microorganisms may also utilize particular GOS structures. However, utilization is species- and strain-dependent and should not be assumed to occur uniformly across all beneficial bacteria.

Microorganisms differ in their ability to recognize glycosidic bonds, transport oligosaccharides, and metabolize the resulting monosaccharides. These differences contribute to variation in microbial responses among individuals.

The structure–function relationship is therefore central to GOS research. A preparation that supports one microbial group in a laboratory fermentation system may not produce the same response in the complex human intestinal ecosystem.

Production of short-chain fatty acids

Fermentation of GOS can generate short-chain fatty acids (SCFAs), including acetate, propionate, and butyrate, either directly or through metabolic interactions between microbial populations.

Bifidobacteria commonly produce acetate, while other organisms may generate butyrate through cross-feeding and utilization of fermentation intermediates. The



precise SCFA profile depends on microbial composition, substrate structure, and environmental conditions.

SCFAs can contribute to intestinal physiology through several mechanisms, including serving as energy substrates for intestinal epithelial cells, influencing luminal pH, and interacting with host signaling pathways. However, an increase in one SCFA does not automatically establish a clinically meaningful health benefit.

IV.HEALTH BENEFITS

Modulation of gut microbiota

One of the most consistently investigated effects of GOS is its capacity to modify intestinal microbial composition, particularly by supporting bifidobacteria. Dose, duration, the initial microbiota, and the ingredient's molecular composition influence this response.

Microbiota changes are useful biological outcomes, but they do not necessarily improve symptoms, reduce disease risk, or improve quality of life. Clinical studies should therefore evaluate microbial composition alongside functional measures and prespecified health outcomes.

Bowel function and stool characteristics

GOS fermentation may affect stool characteristics, intestinal transit, and bowel habits. Fermentation can increase microbial biomass and alter the colon's osmotic and metabolic environment.

The magnitude of these effects depends on intake and individual tolerance. GOS should not be regarded as a universal treatment for constipation or other gastrointestinal disorders without condition-specific clinical evidence.

Mineral absorption and bone-related outcomes

Researchers have investigated fermentable oligosaccharides for their potential to influence calcium and other mineral absorption. Proposed mechanisms include changes in colonic pH and mineral solubility, along with microbiota-mediated effects on intestinal physiology. However, evidence from one oligosaccharide, population, or mineral cannot automatically apply to every GOS product. Studies assessing mineral



balance, longer-term bone outcomes, and relevant confounding variables are needed to determine the practical significance of these mechanisms.

Immune function

GOS may influence immune responses indirectly through changes in microbial activity and intestinal metabolites. Research has explored outcomes such as immune markers, inflammatory signaling, and responses to environmental or dietary challenges.

Interpretation requires caution because changes in immune biomarkers are not equivalent to reduced infection rates or prevention of allergic disease. Clinical claims should be based on adequately powered trials using clearly defined populations and outcomes.

Metabolic health

The intestinal microbiota and its metabolites influence host energy metabolism, glucose regulation, and lipid metabolism. Consequently, researchers have investigated GOS as potential dietary modulators of metabolic health. Preclinical findings suggest mechanistic hypotheses, but human responses can vary. Distinguish the effects of GOS from those of the overall dietary pattern, body-weight changes, and other lifestyle factors. Current evidence does not justify describing GOS as a stand-alone treatment for diabetes, obesity, or metabolic syndrome.

Infant nutrition

Researchers have widely investigated GOS in infant nutrition because of their relationship to the oligosaccharide environment of the developing intestine. They may be added to infant formula, sometimes alongside other prebiotic ingredients. Infant developmental stage, ingredient composition, dosage, and clinical endpoint are important considerations. Commercial GOS are not chemically identical to human milk oligosaccharides, and adding GOS to formula does not make the product equivalent to human milk. Safety and efficacy assessments should be specific to the intended infant population and formulation. Findings from healthy term infants should not automatically be generalized to preterm infants or infants with medical conditions.



Gut–brain interactions

The gut–brain axis provides a plausible framework for investigating whether prebiotic-induced microbial changes influence stress-related, cognitive, or behavioral outcomes. Microbial metabolites, immune signaling, and neural pathways may participate in these interactions.

Nevertheless, evidence linking GOS specifically to clinically meaningful improvements in mood, cognition, or neurological disorders remains insufficient to support broad therapeutic claims. Future work should prioritize controlled human trials and validated psychological or neurological outcomes.

V.APPLICATIONS OF GOS IN FUNCTIONAL FOODS

Dairy products

Dairy foods offer practical opportunities for incorporating GOS because they are familiar delivery vehicles for functional ingredients. Potential applications include milk beverages, fermented milk, yogurt, dairy desserts, and specialized nutritional formulations. GOS may contribute to the fermentable carbohydrate fraction of these products. Evaluate its effects on taste, sweetness, texture, fermentation behavior, and storage stability for each formulation. In fermented dairy products, starter-culture metabolism and GOS utilization may influence the final carbohydrate profile. Therefore, compatibility between the added ingredient and the selected starter culture should be established experimentally.

Infant formula and specialized nutrition

Some infant formulas and specialized nutritional products use GOS. Their inclusion requires consideration of ingredient purity, carbohydrate composition, microbiological quality, regulatory requirements, and population-specific safety data. Formulation research should distinguish the effects of GOS alone from those of blends containing other prebiotic ingredients.

Bakery products and cereal-based foods

GOS can potentially be incorporated into bakery products, cereals, snack bars, and other formulated foods. Processing conditions, especially heat exposure and interactions with other ingredients, may affect product quality and carbohydrate



composition. The impact of GOS on browning reactions, moisture retention, texture, and sensory acceptability should be examined at the intended inclusion level. Product development must also account for the possibility that residual mono- and disaccharides contribute to observed sweetness or browning.

Beverages and nutritional supplements

Formulators can incorporate liquid GOS concentrates and powdered preparations into beverages and dietary formulations. Their suitability depends on solubility, stability, sensory properties, and compatibility with the product matrix.

In high-acid beverages or products subjected to severe heat treatment, formulation studies should determine whether processing alters the oligosaccharide profile.

Synbiotic formulations

Combining a prebiotic with a probiotic produces a formulation commonly described as a synbiotic. GOS may be paired with selected microbial strains where there is a clear scientific rationale for the combination. A successful synbiotic formulation requires evidence that the microorganism remains viable when viability matters, that the substrate is used as intended, and that the combination provides the proposed benefit. Merely adding GOS and a probiotic to the same product does not establish synergistic efficacy.

Safety, Tolerability, and Regulatory Considerations

GOS are generally investigated as food ingredients, but tolerability depends on the dose, product composition, and individual sensitivity. Because they undergo intestinal fermentation, excessive intake may cause gas production, bloating, abdominal discomfort, or changes in bowel habits. Individuals with irritable bowel syndrome or sensitivity to fermentable carbohydrates may experience symptoms at intakes tolerated by others. GOS can be relevant to low-FODMAP dietary management, and their suitability should be assessed in the context of the individual's dietary plan and clinical guidance. A safety assessment should include ingredient identity, purity, residual sugars, microbiological quality, the intended population, and exposure level. Infant nutrition products require particularly careful, population-specific evaluation. Regulatory requirements for ingredient authorization, labeling, and health claims vary across jurisdictions. Evidence supporting a general prebiotic mechanism does not



automatically authorize a specific disease-risk reduction or therapeutic claim. Manufacturers should verify current requirements in each intended market and ensure that product claims are supported by appropriate evidence.

VI.CONCLUSION

Galacto-oligosaccharides are important prebiotic carbohydrates with established relevance to functional food development and substantial potential for further innovation. Their biological effects depend on molecular structure, microbial utilization, fermentation characteristics, and the consumer's physiological context. Producing them through β -galactosidase-mediated transgalactosylation also creates opportunities to convert lactose-rich dairy streams into value-added ingredients. Although GOS are particularly promising for microbiota modulation and selected nutritional applications, evaluate evidence separately for each proposed health outcome. Variability among commercial preparations, individual differences in microbial response, gastrointestinal tolerability, and limitations in long-term clinical evidence remain important considerations.

REFERENCE

1. Gibson GR, Hutkins R, Sanders ME, et al. Expert consensus document: The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of prebiotics. *Nature Reviews Gastroenterology & Hepatology*. 2017;14:491–502.
2. Hutkins R, Walter J, Gibson GR, et al. Classifying compounds as prebiotics—scientific perspectives and recommendations. *Nature Reviews Gastroenterology & Hepatology*. 2024
3. Petrov K, et al. Prebiotic effects of α - and β -galactooligosaccharides: The structure-function relation. *Molecules*. 2025;30(4):803.
4. Costa MA, Schmitz C, de Lima JC, Lehn DN, de Souza CFV. Recent perspectives on the biosynthesis of galacto-oligosaccharides: A systematic review and meta-analysis. *Food Chemistry*. 2025;497:147072
5. Structure, enzymatic production, biological activities, and food applications of galacto-oligosaccharides: A review. *The Journal of Nutrition*. 2025.
6. International Scientific Association for Probiotics and Prebiotics (ISAPP). Prebiotic definition updated by ISAPP. Updated June 21, 2025. Available at:



7. International Scientific Association for Probiotics and Prebiotics (ISAPP). ISAPP elaborates criteria for prebiotics. Updated July 3, 2025. Available at:

8. Marco ML, Cunningham M, Bischoff SC, et al. The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of gut health. *Nature Reviews Gastroenterology & Hepatology*. 2026;23:432–448.