Review article

Wheat bran-derived xylo- and maltooligosaccharides as potential synergistic prebiotics for animal nutrition

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Abstract

Background and Aim. Xylooligosaccharides (XOS) and maltooligosaccharides (MalOS) are promising prebiotic candidates for functional feed additives in animal nutrition. Wheat bran, containing arabinoxylan-rich hemicellulose and residual starch, is a potential source of both oligosaccharide fractions. This review analyzes their structural-functional properties, possible prebiotic synergy, and prospects for use in animal feeding.

Materials and Methods. Wheat bran was considered a plant-derived biomatrix containing arabinoxylans as a source of XOS and residual starch as a potential source of maltooligosaccharides (MalOS). This review analyzed English-language peer-reviewed publications from 2004–2025 on wheat bran composition, XOS and maltooligosaccharide structure, digestive stability, gut microbiota modulation, short-chain fatty acid production, and use in animal nutrition. Searches were conducted in Web of Science, PubMed, and Google Scholar using keywords including wheat bran, xylooligosaccharides, maltooligosaccharides, prebiotic properties, animal nutrition, gut microbiota, fermentation kinetics, and short-chain fatty acids.

Results. The reviewed data indicate that wheat bran is a promising substrate for obtaining two functional oligosaccharide groups: XOS from the arabinoxylan fraction and maltooligosaccharides from residual starch. XOS are resistant to digestive enzymes and can reach the lower intestine, where they serve as substrates for saccharolytic bacteria, whereas maltooligosaccharides may be fermented more rapidly if partially preserved after digestion. The prebiotic effects of XOS are supported by *in vitro* and animal studies, particularly in poultry, whereas evidence for MalOS is more limited and is derived mainly from in vitro studies. Available data indicate the potential of MalOS to modulate gut microbiota and promote short-chain fatty acid production, but these effects require further validation in animals. The combined use of XOS and MalOS may provide complementary prebiotic effects due to differences in their structure, digestive stability, and fermentation rate; however, direct evidence for synergistic action between XOS and MalOS is currently lacking.

Conclusion. Wheat bran is a promising source of XOS- and maltooligosaccharide-containing fractions for functional feed additives. Their combination may support animal gut microbiota, enhance short-chain fatty acid production, strengthen intestinal barrier function, and improve feeding efficiency. Further studies should focus on standardizing fraction composition, optimizing production conditions, and validating XOS-maltooligosaccharide efficacy in *in vitro, in vivo*, and productive animal trials.

Keywords: animal nutrition; maltooligosaccharides; xylooligosaccharides; wheat bran.

Introduction

Gastrointestinal diseases and functional disorders in farm animals remain among the key factors contributing to reduced productivity, impaired feed conversion, increased treatment costs, and higher mortality rates in young animals [1, 2]. The most vulnerable periods include the early postnatal stage in calves, the weaning period in piglets, and the intensive growth phase in poultry, when the intestinal

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microbiota, mucosal barrier function, and digestive enzyme system undergo active restructuring. For example, in a study of dairy calves up to six months of age, diarrhea was the most common disease, with a risk of 25.2%, and accounted for 33.3% of all mortality cases [3].

In pig production, one of the major problems is post-weaning diarrhea, which is associated with abrupt dietary changes, restructuring of the intestinal microbiota, reduced intestinal barrier function, and an increased risk of colonization by enterotoxigenic E. coli strains. This leads to reduced body weight gain, impaired feed conversion, and economic losses [4]. In this regard, current studies emphasize the need for feeding strategies aimed at supporting the gut microbiota, strengthening the intestinal barrier, and reducing dependence on antibiotics and pharmacological doses of zinc oxide [5, 6].

In poultry production, necrotic enteritis associated with *Clostridium perfringens* is a significant example of intestinal pathology. This disease disrupts intestinal integrity, impairs nutrient absorption, reduces body weight gain, and increases the feed conversion ratio [7]. According to recent reviews, necrotic enteritis is among the most economically important intestinal diseases in poultry, with global annual losses estimated at approximately USD 6 billion [8].

In the light of this, there is a growing need for functional feed components capable of supporting the intestinal microbiota of animals without the direct use of antibiotic growth promoters [9]. These components include prebiotics - substrates selectively utilized by the microbiota in both monogastric and ruminant animals [10, 11]. Such substrates promote the growth of beneficial bacteria, stimulate the production of short-chain fatty acids, reduce intestinal pH, strengthen the epithelial barrier, improve the stability of the intestinal ecosystem, and may contribute to improved animal performance [12].

Functional oligosaccharides, including xylooligosaccharides (XOS) and maltooligosaccharides, are of particular interest among feed prebiotics [13]. XOS are non-digestible xylan-derived substrates capable of reaching the lower intestinal tract, where they are utilized by saccharolytic bacteria, including *Bifidobacterium* and *Lactobacillus* [14]. Evidence on the use of XOS in animal production has already accumulated, particularly in poultry. A meta-analysis of broiler studies, including 36 peer-reviewed papers published between 2000 and 2024, showed that XOS supplementation increased average daily gain by 6.445% and average daily feed intake by 1.544%, while reducing the feed conversion ratio by 7.147% compared with the control [15]. In laying hens, dietary inclusion of XOS for 24 weeks was associated with improved intestinal morphology, increased cecal concentrations of butyric and isovaleric acids, greater bacterial diversity, and an increased relative abundance of *Lactobacillus* and *Bifidobacteriaceae [*16].

Maltooligosac charides have been studied in animal nutrition to a much lesser extent than XOS, fructooligosaccharides, galactooligosaccharides, or mannan-oligosaccharides; therefore, their feed-related potential should be considered cautiously – as a promising but still insufficiently validated direction [17, 18]. From a scientific perspective, interest in maltooligosaccharides (hereafter referred to as MalOS to avoid confusion with mannan-oligosaccharides) is associated with their potential role as starch-derived substrates with faster fermentative availability, whereas XOS may provide a more prolonged effect on the intestinal microbiota. These differences in structure and fermentation kinetics form the basis for the hypothesis of complementary effects of XOS and MalOS in feed compositions [19, 20].

Wheat bran is a promising raw material for obtaining such oligosaccharide fractions. It is an accessible by-product of flour milling that contains an arabinoxylan-rich hemicellulosic fraction and residual starch. Arabinoxylans can serve as a source of XOS, whereas the residual starch fraction can be used to obtain MalOS [21]. Experimental data confirm the high potential of wheat bran as a source of XOS: after enzymatic treatment of destarched and deproteinized wheat bran, *Wang* et al. obtained XOS with a purity of approximately 95%, a degree of polymerization of DP2–DP7, and a yield of about 31.2% based on the mass of wheat bran insoluble dietary fiber [22]. Similar data were obtained by *Kumari* et al., who reported a maximum XOS yield of 374 mg/g from raw wheat bran and 419 mg/g from wheat bran-extracted xylan [23]. These values indicate that wheat bran should be considered not only as a conventional feed component but also as a promising bioresource for producing concentrated XOS fractions potentially suitable for functional feed additives.

The practical interest in XOS is supported not only by experimental studies but also by the development of the feed prebiotic market. A recent review by *Ali* et al. indicates that XOS are used

in various sectors, including the feed industry, and commercial catalogues already offer feed-grade XOS products, such as powdered forms containing 35% XOS for livestock, poultry, pet food, and aquaculture [24]. However, in most commercial descriptions, the raw material source of XOS is not disclosed; therefore, such products cannot automatically be considered wheat bran-derived.

In contrast to XOS, quantitative data and commercial feed solutions for MalOS specifically obtained from the residual starch of wheat bran are much more limited. Nevertheless, experimental data on MalOS as functional starch-derived oligosaccharides indicate their potential significance. In the study by *Jang* et al., enzymatic treatment of starch-containing raw material resulted in a MalOS content of 52.34%, and the fraction contained 21.74% maltotriose, 18.84% maltotetraose, and 11.76% maltopentaose. The addition of 1% MalOS stimulated the growth of *Bifidobacterium breve,* while 2% MalOS during fecal fermentation promoted increased production of short-chain fatty acids and altered the microbial profile [19]. A comparative study by *Cheon* et al. also showed that MalOS have moderate digestibility: after *in vitro* digestion, the reducing sugar content was 17.55%, and released glucose accounted for 10.3%, indicating partial preservation of the fraction for subsequent microbial fermentation [25]. Therefore, with respect to wheat bran, it is most appropriate to state that XOS already have confirmed technological and feed-related potential, whereas MalOS derived from the residual starch of wheat bran represent a promising additional fraction requiring further standardization, yield assessment, and validation in trials with productive animals.

Thus, wheat bran has a dual raw-material potential: its arabinoxylan-rich fraction can be used to obtain XOS, while its residual starch fraction can serve as a source of MalOS. The combination of these oligosaccharides is of scientific interest from the perspective of feed biotechnology, since differences in their chemical structure, digestive stability, and rate of microbial fermentation may provide complementary prebiotic effects. A potential XOS–MalOS composition may be directed toward supporting the intestinal microbiota of animals, stimulating beneficial bacteria, enhancing short-chain fatty acid production, maintaining intestinal barrier function, and improving feeding efficiency. However, the integrated use of wheat bran as a single raw material source of XOS and MalOS, as well as the evaluation of their combined effects in animal production, remains insufficiently studied.

This review aims to analyse wheat bran as a source of xylo- and maltooligosaccharides, to discuss their structural – functional properties, potential complementary prebiotic effects, and prospects for application in animal nutrition.

Materials and Methods

Source Material

Wheat bran, a by-product of the flour-milling industry, was considered in this review as a complex plant-derived biomatrix. Its composition includes an arabinoxylan-rich hemicellulosic fraction and a residual starch fraction retained after grain milling. The presence of these biopolymers provides a basis for the targeted transformation of wheat bran into functional oligosaccharide fractions.

Wheat bran was evaluated as an accessible and promising bioresource for obtaining value-added oligosaccharide products, including xylooligosaccharides (XOS) and maltooligosaccharides (MalOS). The arabinoxylan fraction represents the main substrate for XOS formation, whereas residual starch may serve as a source of MalOS through the action of amylolytic enzymes.

Data Sources and Search Strategy

This study was designed as a narrative literature review. Scientific publications related to the biotechnological processing of wheat bran, the production of xylo- and maltooligosaccharides, and the evaluation of their functional and prebiotic properties were analysed. Particular attention was given to studies addressing the structure-dependent properties of XOS and MalOS, including degree of polymerization, type of glycosidic linkages, presence of structural substituents, resistance to digestive enzymes, and microbial fermentation patterns.

The review included studies describing the effects of oligosaccharides on gut microbiota, the growth of beneficial bacteria such as Bifidobacterium and Lactobacillus, the formation of short-chain fatty acids, and differences in fermentation kinetics among individual oligosaccharide fractions. Experimental *in vitro* and *in vivo* studies, data from animal nutrition trials, review articles, and book chapters were considered. The main time frame of the analysed literature covered publications from 2004 to 2025.

Search Tools and Keywords

The literature search was conducted using the international databases Web of Science, PubMed, and Google Scholar. The following keywords and their combinations were used: wheat bran, xylooligosaccharides (XOS), maltooligosaccharides, malto-oligosaccharides, MalOS, prebiotic properties, animal nutrition, feed additives, gut microbiota, fermentation kinetics, short-chain fatty acids, enzymatic hydrolysis, arabinoxylan, starch hydrolysis, and functional oligosaccharides.

The search was mainly limited to English-language peer-reviewed publications. Priority was given to studies containing experimental data on the production of oligosaccharides from plant-derived raw materials, characterization of their structure and degree of polymerization, and assessment of their functional effects. Additional attention was paid to studies discussing the possible combined use of XOS and MalOS as a basis for complementary or potentially synergistic prebiotic effects on the gut microbiota of farm animals.

The reliability of the selected studies was assessed based on the type of publication, the presence of clearly described experimental methods and controls, and the relevance of the reported data to the objectives of this review. Greater weight was given to peer-reviewed experimental studies and recent systematic or comprehensive reviews. Where evidence was limited or indirect, the corresponding conclusions were interpreted cautiously and identified as requiring further experimental validation.

Results

Chemical Composition and Biopolymeric Structure of Wheat Bran

Wheat bran (Triticum aestivum) is a multilayered plant structure separated from the endosperm during grain milling [26]. Its morphological and chemical composition is determined by the structural characteristics of the outer layers of the wheat kernel, including the pericarp, seed coat, hyaline layer, and aleurone layer. These anatomical fractions are characterized by dense cell walls, a high dietary fiber content, and a complex spatial organization of biopolymers, which determine both the technological resistance of wheat bran and its value as a raw material for biotechnological processing [27].

From a chemical perspective, wheat bran is a multicomponent plant biomatrix dominated by non-starch polysaccharides, primarily arabinoxylans, cellulose, and other cell-wall components [28]. In addition, wheat bran contains residual starch, proteins, lipids, minerals, B vitamins, phytic acid, and phenolic compounds. This combination of components makes wheat bran not only a source of dietary fiber but also a promising substrate for the production of value-added products, including functional oligosaccharides [29].

According to review studies, wheat bran usually contains a substantial proportion of non-starch polysaccharides, residual starch, proteinaceous compounds, lipids, and mineral components. The quantitative ratio of these fractions may vary depending on wheat cultivar, growing conditions, degree of grain milling, and processing technology [30, 31]. Therefore, wheat bran should not be regarded as a homogeneous by-product, but rather as a variable biopolymeric system whose properties are determined by both the original grain material and the processing method [32].

The biopolymeric structure of wheat bran is formed through close interactions among polysaccharides, proteins, and phenolic compounds within the cell wall. Arabinoxylans and cellulose constitute the structural framework of the grain outer layers, whereas proteins, lignin-like components, and phenolic acids further reinforce the cell-wall matrix [33]. This organization provides high mechanical strength to wheat bran, but at the same time limits enzymatic access to the target polysaccharide substrates. Therefore, efficient release of oligosaccharide fractions requires pretreatment and controlled enzymatic hydrolysis [34].

Of particular importance for the production of xylo- and maltooligosaccharides is the presence of two distinct carbohydrate fractions in wheat bran: the arabinoxylan fraction and the starch fraction. Arabinoxylans are the major hemicellulosic components of the outer grain layers and serve as potential substrates for the formation of xylooligosaccharides, whereas residual starch retained in bran due to incomplete separation of the endosperm can be used to obtain maltooligosaccharides. Thus, wheat bran has dual raw-material potential, serving as a source of both hemicellulose-derived and starch-derived oligosaccharides [29, 34].

Therefore, wheat bran should be considered a multicomponent plant biomatrix in which structural polysaccharides, residual starch, proteins, lipids, minerals, and phenolic compounds form a complex cell-wall system. The combined presence of arabinoxylan and starch fractions determines its value as a raw material for obtaining functional oligosaccharides, including xylooligosaccharides (XOS) and maltooligosaccharides (MalOS), and justifies further analysis of individual wheat bran fractions in the following subsections.

Chemical Structure of Xylooligosaccharides

Xylooligosaccharides (XOS) are short-chain oligosaccharides composed predominantly of D-xylose residues linked by β-(1→4)-glycosidic bonds. The basic monomeric unit of XOS is D-xylose, with the molecular formula $C_5H_{10}O_5$. Condensation of several xylose residues results in the formation of linear XOS with different chain lengths, among which the most common are xylobiose ($C_{10}H_{18}O_9$), xylotriose ($C_{15}H_{26}O_{13}$), xylotetraose ($C_{20}H_{34}O_{17}$), xylopentaose ($C_{25}H_{42}O_{21}$), and xylohexaose ($C_{30}H_{50}O_{25}$). In general, linear XOS can be represented by the formula $C_{5n}H_{8n}+2O_{4n}+1$, where n corresponds to the degree of polymerization (DP). For the most extensively studied XOS fractions, the DP usually ranges from DP2 to DP6 [24, 35].

Structurally, XOS may occur either as linear xylooligosaccharides or as substituted forms, primarily arabino-xylooligosaccharides (AXOS), which are formed during the partial hydrolysis of arabinoxylans. Enzymatic hydrolysis of xylan using xylanases is considered an effective approach for the production of XOS, as it enables selective cleavage of the β-(1→4)-xylosidic linkages in the xylan backbone under mild reaction conditions [36, 37]. In AXOS, side substituents are attached to the xylan backbone, most commonly α-L-arabinofuranose residues located at the O-2 and/or O-3 positions of xylose units. The presence of these substituents, as well as possible acetyl or phenolic moieties, substantially influences the physicochemical properties of the oligosaccharides, including their solubility, molecular weight, hydration capacity, and accessibility for microbial fermentation [38].

As shown in Figure 1, the structural organization of XOS includes the D-xylose monomeric unit, linear oligomers with different degrees of polymerization ranging from xylobiose to xylohexaose, their formation through partial hydrolysis of xylan/arabinoxylan, and substituted AXOS forms containing lateral arabinose residues. The same figure schematically illustrates that XOS are not hydrolysed during digestion in the upper gastrointestinal tract, whereas their main transformation occurs during microbial fermentation in the large intestine.

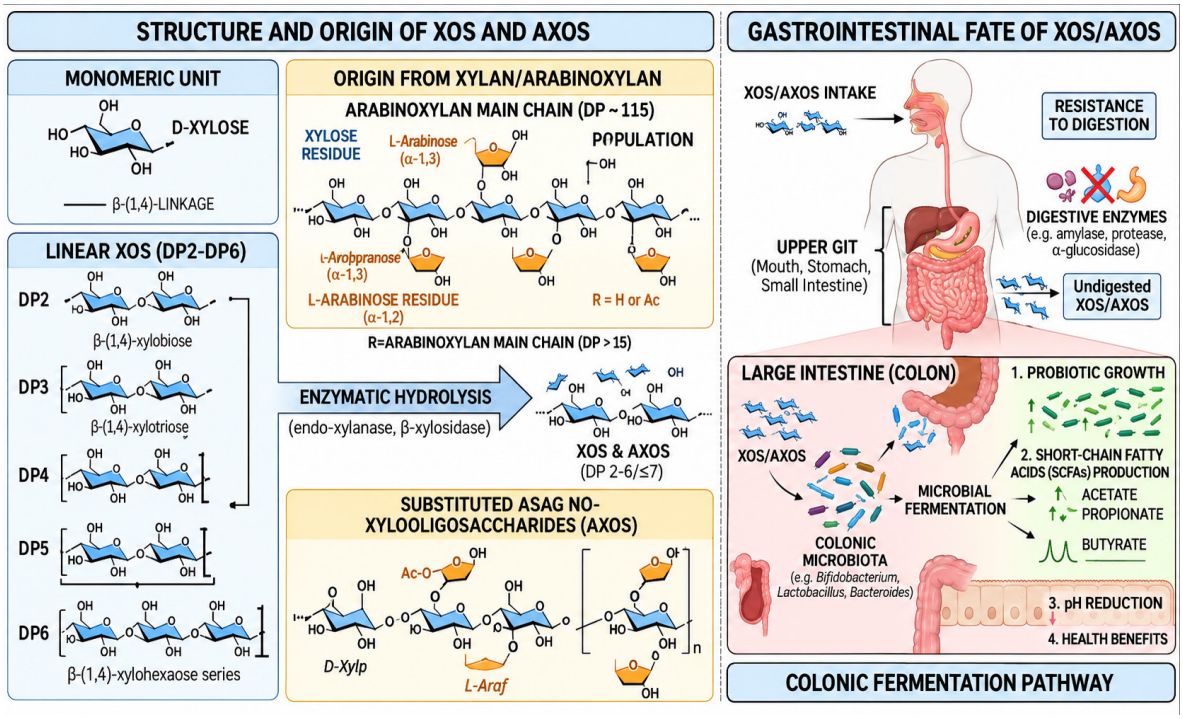

Figure 1. Structure, origin, and gastrointestinal transformation of xylo- and arabino-xylooligosaccharides in animals

From a chemical perspective, the key parameters determining the properties of XOS are the type of glycosidic linkage, degree of polymerization, and degree of substitution. Linear XOS, represented by the repeating fragment [β-D-Xylp-(1→4)] n, differ from substituted AXOS in that the latter contain additional side groups capable of altering the spatial conformation of the molecule and its interactions with water and enzymes. In general, short-chain XOS fractions with DP2–DP4 are characterized by higher solubility and greater accessibility for microbial utilization, whereas longer or more highly substituted forms may exhibit slower fermentation and a more prolonged effect in the intestinal environment [39].

A fundamental feature of XOS is that β-(1→4)-xylosidic linkages are not hydrolysed by digestive enzymes in the upper gastrointestinal tract of animals. Unlike α-glucans, which are susceptible to amylase-mediated hydrolysis, XOS retain their structure during passage through the stomach and small intestine and are therefore classified as non-digestible oligosaccharides. This property enables their delivery to the lower gastrointestinal tract, where they become substrates for the fermentative activity of the intestinal microbiota. Consequently, XOS are regarded as promising prebiotic compounds, while their structural parameters – primarily DP and the presence of substituents – are key factors determining the selectivity and intensity of microbial fermentation [35, 38].

Thus, xylooligosaccharides represent a structurally heterogeneous group of non-digestible oligosaccharides whose functional properties are determined by chain length, the presence of β-(1→4)-glycosidic linkages, and the degree of substitution of the xylan backbone. The occurrence of both linear XOS and substituted AXOS expands their physicochemical and biological characteristics by influencing solubility, resistance to digestive enzymes, and availability to the intestinal microbiota. Owing to their stability in the upper gastrointestinal tract and their ability to undergo microbial fermentation in the lower intestine, XOS are considered promising prebiotic compounds, the effectiveness of which largely depends on the degree of polymerization and molecular organization.

Chemical Structure of Maltooligosaccharides

Maltooligosaccharides (malto-oligosaccharides, MalOS) are starch-derived homooligosaccharides composed of D-glucose residues linked predominantly by α-(1→4)-glycosidic bonds. The basic monomeric unit of these compounds is D-glucose, with the molecular formula $C_6H_{12}O_6$, while linear MalOS can generally be represented by the formula $C_{6n}H_{10n}+_2O_{5n}+1$, where n corresponds to the degree of polymerization. Typical representatives of this group include maltose ($C_{12}H_{22}O_{11}$; DP2), maltotriose ($C_{18}H_{32}O_{16}$; DP3), maltotetraose ($C_{24}H_{42}O_{21}$; DP4), maltopentaose ($C_{30}H_{52}O_{26}$; DP5), and maltohexaose ($C_{36}H_{62}O_{31}$; DP6). In recent reviews, MalOS are generally described as compounds containing approximately 3–10 glucose residues, although in technological schemes maltose is often also included in maltooligosaccharide fractions as a DP2 component [18].

Unlike XOS, which are formed from the xylan backbone of hemicellulose, MalOS are produced through partial hydrolysis of starch, a polysaccharide composed of amylose and amylopectin. Amylose is a predominantly linear α-(1→4)-linked glucan, whereas amylopectin has a branched structure due to α-(1→6) linkages at branching points. Therefore, the profile of the resulting MalOS depends not only on the degree of hydrolysis but also on the amylose-to-amylopectin ratio in the original starch, the accessibility of starch granules, and the presence of branched dextrins. In the case of incomplete amylopectin degradation, limit dextrins or fractions containing residual α-(1→6) linkages may remain in the hydrolysate, affecting the molecular-weight distribution and functional properties of the final product (Figure 2) [40].

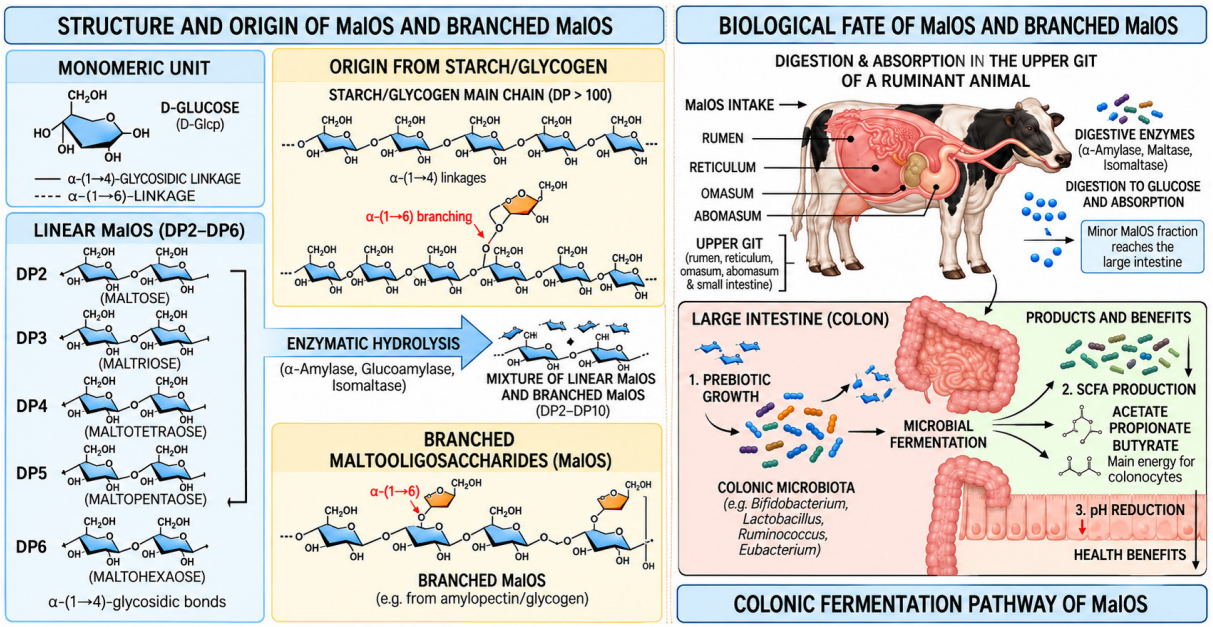

Figure 2. Structure, origin, and biological transformation of maltooligosaccharides (MalOS) in the gastrointestinal tract of farm animals

The formation of MalOS is determined by the specificity of amylolytic enzymes. α-amylases catalyse the endohydrolysis of internal α-(1→4) linkages in starch, resulting in the formation of dextrins, maltose, maltotriose, and other short glucose oligomers [41, 42]. In addition to conventional α-amylases, maltooligosaccharide-forming amylases are of particular importance, as they can selectively generate products with a defined degree of polymerization, such as maltotriose, maltotetraose, maltopentaose, or maltohexaose. This is essential for obtaining standardized MalOS fractions, since the physiological and technological properties of maltooligosaccharides depend not only on their general glucose-based nature but also on the distribution of individual DP fractions [18, 43].

From the perspective of food chemistry, MalOS occupy an intermediate position between readily digestible starch hydrolysis products and potentially functional oligosaccharide fractions. Since α-(1→4)-glycosidic linkages are accessible to human digestive enzymes, part of the MalOS fraction may be hydrolysed in the upper gastrointestinal tract by salivary and pancreatic α-amylases, as well as by brush-border enzymes of the small intestine. However, their degree of digestibility depends on chain length, fraction structure, food matrix, and associated components. Therefore, MalOS should not automatically be classified as completely non-digestible compounds: their prebiotic potential requires evaluation of digestive stability and the ability of preserved fractions to reach the large intestine [25, 40].

Experimental data confirm that certain MalOS-containing fractions may exhibit prebiotic-like effects. In the study by *Jang* et al., MalOS produced with the involvement of amylase contained substantial proportions of maltotriose, maltotetraose, and maltopentaose; these fractions were evaluated for their resistance to *in vitro* digestion, their ability to stimulate the growth of *Bifidobacterium breve*, and their capacity to alter the fermentation profile of human faecal microbiota [19]. In a comparative study by *Cheon* et al., MalOS were evaluated together with other commercially available prebiotic oligosaccharides; the authors showed that MalOS demonstrated moderate enzymatic digestibility but, during subsequent faecal fermentation, were able to influence microbiota composition and the metabolomic profile [25].

In a broader context, MalOS belong to the group of gluco-oligosaccharides, for which structure, synthesis methods, purification, digestive stability, and potential prebiotic effects have been actively studied in recent years. The review by *Zeng* et al. emphasizes that the prebiotic properties of gluco-oligosaccharides depend on the number of glucose residues, the type of O-glycosidic linkages, the degree of polymerization, and selective fermentability by beneficial bacteria; however, their effects remain more variable compared with classical non-digestible prebiotics [43]. This point is particularly

important for MalOS, since their functional activity is determined not only by the presence of α-(1→4) linkages but also by the proportion of the fraction that remains after digestion and becomes available for microbial fermentation.

Thus, the chemical structure of MalOS is determined by the glucose nature of the monomeric units, the predominance of α-(1→4)-glycosidic linkages, the degree of polymerization, and the characteristics of enzymatic production from starch. Unlike XOS, maltooligosaccharides are more susceptible to digestive enzymes in humans; however, certain MalOS fractions may persist after digestion and participate in microbial fermentation. Therefore, MalOS should be regarded as structure-dependent functional oligosaccharides whose prebiotic potential is determined by the balance between digestibility, degree of polymerization, fraction composition, and the ability to support the growth of beneficial members of the intestinal microbiota.

Prebiotic Effects and the Influence of XOS and MalOS on the Gut Microbiota

The prebiotic effect of oligosaccharides is associated with their ability to reach the large intestine in an unchanged or partially preserved form and serve as selective substrates for metabolically active members of the gut microbiota. The most important effects include stimulation of beneficial bacteria, primarily representatives of the genera *Bifidobacterium* and *Lactobacillus*, enhanced production of short-chain fatty acids (SCFA), reduction of intestinal pH, inhibition of opportunistic microorganisms, and support of intestinal epithelial barrier function [44, 45].

Effects of XOS on Bifidobacterium, Lactobacillus, and the Microbiota Profile

Xylooligosaccharides (XOS) are among the most extensively studied non-digestible oligosaccharides with pronounced bifidogenic potential. Their β-(1→4)-linked xylosyl backbone is not degraded by human digestive enzymes but can be utilized by specific groups of intestinal bacteria possessing the corresponding xylosidases, xylanases, and arabinofuranosidases. Recent review studies indicate that XOS can selectively stimulate the growth of beneficial members of the gut microbiota, primarily *Bifidobacterium* and certain lactic acid bacteria, enhance the production of short-chain fatty acids, and limit the development of opportunistic microorganisms; however, the magnitude of these effects depends on the degree of polymerization, raw material source, production method, and presence of structural substituents [13, 20, 46].

Of particular importance is that different bacterial species utilize XOS and AXOS unevenly. For example, *Bifidobacterium adolescentis* is able to utilize both unsubstituted XOS and arabinose-substituted AXOS, whereas certain representatives of *Lactobacillus* may ferment branched forms less efficiently. This is explained by differences in the enzymatic machinery of microorganisms: bifidobacteria can produce enzymes capable of removing arabinose substituents, thereby increasing the accessibility of the xylan backbone for further degradation. Such structure-dependent differences create prerequisites for selective modulation of the microbiota and the formation of cross-feeding interactions among different bacterial groups [36, 47].

Data from *in vitro* and clinical studies confirm that XOS can increase the relative abundance of *Bifidobacterium* and certain lactic acid bacteria, as well as shift the microbiota composition toward a profile associated with improved intestinal homeostasis. Review data indicate that in studies using individual strains and fecal cultures, XOS promoted the growth of *Bifidobacterium, Lactobacillus, Bacteroides*, and other saccharolytic microorganisms, while in some cases limiting the growth of *Escherichia coli, Salmonella typhimurium, Staphylococcus aureus,* and other opportunistic bacteria [13, 38].

Prebiotic Potential of MalOS and Features of Their Microbial Fermentation

Maltooligosaccharides (MalOS) have been studied as prebiotic compounds less extensively than XOS, fructooligosaccharides, or inulin; however, the available data indicate their functional potential. Unlike XOS, MalOS consist of α-(1→4)-linked glucose residues, and therefore part of these fractions may be accessible to human digestive enzymes. Nevertheless, the stability of certain MOS-containing fractions in the in vitro digestion models and their ability to be utilized by fecal microbiota indicate their possible involvement in prebiotic fermentation [19].

In the study by *Jang* et al., MalOS fractions obtained using amylase and containing substantial proportions of maltotriose, maltotetraose, and maltopentaose stimulated the growth of *Bifidobacterium breve* when used as a carbon substrate. In addition, fermentation involving human fecal microbiota was associated with changes in the microbial metabolic profile and SCFA formation. These data

suggest that MOS can be considered not only as intermediate products of starch hydrolysis but also as potential functional substrates for specific members of the intestinal microbiota [19].

Comparative evaluation of commercial prebiotic oligosaccharides in an *in vitro* gut model also indicates that MOS can influence the microbial ecosystem, although their effects differ from those of classical non-digestible substrates. In the study by *Cheon* et al., MalOS were compared with fructooligosaccharides, agar-derived fructooligosaccharides, and resistant maltodextrin; the authors showed that MOS exhibited moderate digestibility by digestive enzymes but, during subsequent fecal fermentation, contributed to changes in *Bifidobacterium* abundance and in the metabolomic profile of the intestinal model [25].

Formation of Short-Chain Fatty Acids

A key functional outcome of microbial fermentation of XOS and MalOS is the formation of short-chain fatty acids, primarily acetate, propionate, and butyrate. SCFA are formed in the large intestine during the fermentation of dietary components that have not been digested or absorbed in the small intestine; acetate, propionate, and butyrate are the most abundant SCFA and constitute the major acid pool in the colon [48].

XOS are typically associated with pronounced acetate production as one of the main products of bifidobacterial metabolism. Acetate can then serve as a substrate for other bacteria, including butyrate-producing microorganisms such as *Faecalibacterium prausnitzii, Anaerostipes, Eubacterium,* and *Roseburia*. This cross-feeding mechanism explains why stimulation of bifidobacteria by prebiotics may indirectly enhance butyrate formation and support the metabolic stability of the intestinal ecosystem [47].

MalOS, in turn, may be incorporated more rapidly into fermentative metabolism, provided that part of the fraction remains after digestion. In *in vitro* studies, MalOS-containing fractions were associated with increased production of acetate, propionate, and butyrate, indicating their ability to contribute to the energetic and metabolic support of the intestinal microbiota [19, 25].

Support of the Intestinal Barrier and Immunometabolic Significance

Short-chain fatty acids are not only end-products of fermentation but also important signaling molecules that influence the state of the intestinal barrier. Butyrate serves as an energy substrate for colonocytes, participates in the regulation of tight-junction protein expression, reduces inflammatory activity, and supports the integrity of the epithelial layer. Acetate and propionate are also involved in the regulation of pH, metabolic pathways, and immune responses, making SCFA an important link between diet, microbiota, and the state of the intestinal mucosa [48, 49].

From this perspective, the prebiotic action of XOS and MalOS is realized not only through an increase in the abundance of individual beneficial bacteria but also through changes in the metabolic activity of the entire microbial ecosystem. Increased SCFA production contributes to a reduction in intestinal pH, which may limit the growth of pH-sensitive pathobionts, while also supporting the epithelial barrier and local immune homeostasis. Therefore, evaluation of XOS and MalOS should include not only analysis of *Bifidobacterium* and *Lactobacillus* growth, but also determination of the SCFA profile, indicators of barrier function, and markers of the inflammatory response.

The combined study of XOS and MalOS is of particular interest because these oligosaccharides differ in chemical structure, resistance to digestive enzymes, and probable rate of microbial fermentation. XOS, as β-linked non-digestible xylan-derived oligosaccharides, may provide a more selective and prolonged stimulation of bifidobacteria and other saccharolytic bacteria. MalOS, as α-(1→4)-linked starch-derived oligosaccharides, may potentially be incorporated more rapidly into microbial fermentation, provided that they are partially preserved after digestion. This difference creates a basis for complementary effects: XOS may support selective bifidogenic activity, whereas MalOS may contribute to an earlier fermentative response and SCFA production [19, 38].

Thus, XOS and MalOS may be regarded as functionally distinct and potentially complementary substrates. The prebiotic effects of XOS are supported by substantially broader experimental evidence, whereas the functional effects of MalOS have been demonstrated mainly in vitro and require further validation. Their potential complementary action should therefore be considered a hypothesis requiring direct experimental confirmation.

Potential Synergy between XOS and MalOS

The potential synergy between xylooligosaccharides (XOS) and maltooligosaccharides (MalOS) is associated with the fact that these compounds differ in chemical nature, resistance to digestive enzymes, and, presumably, the rate of microbial fermentation in the large intestine. XOS are β-(1→4)-linked xylan-derived oligosaccharides and more closely meet the criteria for non-digestible prebiotic substrates, whereas MalOS are α-(1→4)-linked glucose oligomers, some of which may undergo digestive hydrolysis, while certain fractions can persist and become involved in microbial fermentation. Therefore, their joint consideration makes it possible to formulate a hypothesis of complementary action: MalOS may provide an earlier fermentative response, whereas XOS may exert a more selective and prolonged effect on the intestinal microbiota [19, 20].

From the perspective of fermentation kinetics, XOS and MalOS may perform different functions within a single prebiotic composition. MalOS, as starch-derived oligosaccharides, are more accessible to amylolytic and microbial metabolism; therefore, if part of the fraction remains after digestion, they may be incorporated into fermentation processes more rapidly. In the study by *Jang* et al., a MalOS-containing fraction composed of maltotriose, maltotetraose, and maltopentaose stimulated the growth of *Bifidobacterium breve* and altered the fermentation profile of human fecal microbiota *in vitro* [19]. In a comparative in vitro gut model, MalOS were also evaluated among commercially available prebiotic oligosaccharides and demonstrated the ability to influence the microbiome and metabolomic profile after fecal fermentation [25].

In contrast, XOS are characterized by greater resistance to human digestive enzymes and can reach the large intestine as substrates for bacteria possessing enzymes capable of degrading the xylan backbone. Their fermentation largely depends on the degree of polymerization, the presence of arabinose substituents, and the structure of the original oligosaccharide fraction. Recent review studies show that XOS can selectively stimulate the growth of *Bifidobacterium* and other saccharolytic bacteria, increase the formation of short-chain fatty acids, and limit the development of opportunistic microorganisms [13, 20, 46].

The concept of XOS–MalOS synergy is consistent with the broader principle of combining carbohydrate substrates with different fermentation rates. *Canfora* et al. demonstrated that the combination of rapidly and slowly fermentable dietary fibers can be considered an approach to enhance distal colonic fermentation and increase acetate production in the large intestine [50]. By analogy with this approach, it can be assumed that MalOS may provide a more rapid onset of microbial fermentation, whereas XOS may support more prolonged substrate utilization and more sustained stimulation of saccharolytic bacteria.

An important mechanism underlying the potential complementary action of XOS and MalOS is the formation of short-chain fatty acids, including acetate, propionate, and butyrate. These metabolites participate in the energy supply of colonocytes, pH regulation, maintenance of the intestinal barrier, and immunometabolic regulation [48] In addition, acetate and lactate produced during bifidobacterial metabolism can be utilized by butyrate-producing bacteria, including representatives of *Faecalibacterium, Anaerostipes, Eubacterium*, and *Roseburia*. This cross-feeding mechanism explains why stimulation of bifidobacteria may indirectly enhance butyrate formation and support the metabolic balance of the intestinal ecosystem [47].

From this perspective, the combination of XOS and MalOS should not be regarded as a simple sum of two oligosaccharides, but rather as a potential substrate system acting at different levels. MalOS may more rapidly provide an available carbon substrate for part of the microbial community, whereas XOS may maintain more selective bifidogenic activity and create conditions for subsequent cross-feeding of butyrate-producing bacteria. As a result, more balanced SCFA formation, a reduction in intestinal pH, and maintenance of the functional stability of the microbiota may be achieved. However, this assumption should be regarded as a scientifically grounded hypothesis, since direct studies of the specific combination of XOS and MalOS obtained from a single raw material source remain insufficient.

The use of wheat bran as a single raw material source for such a combination is of particular interest. The arabinoxylan fraction of wheat bran can serve as a basis for obtaining XOS and AXOS, whereas residual starch can be directionally transformed into MalOS. This creates a technological prerequisite for producing a complex oligosaccharide composition from one accessible agro-industrial

resource. In contrast to approaches in which different prebiotics are obtained from different raw materials and subsequently mixed, the use of wheat bran makes it possible to consider XOS and MalOS as interrelated products of the deep enzymatic processing of a single biomatrix.

Thus, the potential synergy between XOS and MalOS may be determined by three main factors: differences in resistance to digestion, differences in the rate of microbial fermentation, and the possibility of establishing cross-feeding between primary oligosaccharide degraders and secondary producers of short-chain fatty acids. Experimental confirmation of this hypothesis requires studies involving in vitro digestion modelling, fecal fermentation, dynamic assessment of *Bifidobacterium* and *Lactobacillus* growth, determination of SCFA profiles, and comparison of the individual and combined effects of XOS, MalOS, and XOS–MalOS compositions.

Discussion

Wheat bran is of considerable interest as an accessible raw material for obtaining functional oligosaccharide ingredients, since its biopolymeric matrix contains both arabinoxylan fractions suitable for the production of xylooligosaccharides (XOS) and residual starch that can be used for the formation of maltooligosaccharides (MalOS). This approach is consistent with the modern concept of deep processing of cereal by-products, in which low-cost raw materials are converted into value-added products. XOS- and MalOS-containing fractions may be used in the development of functional foods, nutraceuticals, specialized nutrition products, and microbiome-oriented ingredients aimed at supporting the intestinal microbiota and the metabolic activity of the large intestine [34, 44].

The practical application of XOS and MalOS may cover several areas. In the food industry, such ingredients can be incorporated into bakery and cereal products, fermented dairy beverages, functional snacks, powdered mixtures, and specialized nutrition products. XOS are of interest as prebiotic oligosaccharides that are more resistant to digestive enzymes, capable of reaching the large intestine and being utilized by saccharolytic bacteria. MalOS, in turn, may be considered starch-derived oligosaccharides with potentially faster fermentative availability, provided that part of the fraction is preserved after digestion. In this regard, their combination may be promising for the development of compositions with different fermentation rates and a more balanced effect on the microbiota [13, 19].

A separate applied direction is the use of oligosaccharides in livestock and poultry production. In farm animal nutrition, prebiotics are considered functional feed additives aimed at maintaining intestinal microbiota, enhancing intestinal barrier function, improving productivity, and reducing dependence on antibiotic growth promoters. Reviews on feed prebiotics indicate that various non-digestible carbohydrates are used in animal diets, including fructooligosaccharides, galactooligosaccharides, isomaltooligosaccharides, xylooligosaccharides, and other substrates capable of modulating the gut microbiota [10]. This review emphasizes that prebiotics and synbiotics are used primarily to maintain the balance of the intestinal microbiota in animals and as alternatives to antibiotic growth promoters.

The most convincing recent data in the animal nutrition field have been obtained for XOS, particularly in poultry production. A meta-analytical study on broilers, which included 36 peer-reviewed studies published between 2000 and 2024, showed that XOS supplementation increased average daily gain and feed intake and reduced the feed conversion ratio compared with the control [15]. According to this study, XOS increased ADG by 6.445% and ADFI by 1.544%, while reducing FCR by 7.147%, indicating their potential to improve broiler productivity.

In laying hens, dietary XOS supplementation for 24 weeks was also associated with positive changes in productivity and intestinal status. In the study by *Xiong* et al., XOS increased egg production during the early experimental period, improved small intestinal morphology, increased butyric and isovaleric acid concentrations in the cecum, enhanced bacterial diversity, and was associated with an increased proportion of *Firmicutes, Bifidobacteriaceae,* and *Lactobacillus* [16]. These data confirm that XOS may act not only as a source of fermentable substrate but also as a factor influencing intestinal morphology and the profile of microbial metabolites.

Studies of XOS under infectious or inflammatory stress are of particular interest. Ren et al. showed that XOS supplementation attenuated growth retardation and intestinal damage in broiler chickens challenged with avian pathogenic *Escherichia col*i; XOS also reduced intestinal APEC colonization, increased *Lactobacillus levels*, and elevated acetate, butyrate, and valerate concentrations in the

cecum [51]. These findings suggest that XOS may be considered not only as growth- and productivity-oriented additives but also as potential tools for supporting intestinal barrier function under pathogenic challenge.

Maltooligosaccharides require more cautious consideration in the context of animal nutrition. In feed literature, the abbreviation MOS is often used to denote mannan-oligosaccharides; therefore, when discussing maltooligosaccharides specifically, it is advisable to write the term in full or use the abbreviation MalOS. Unlike XOS, direct recent studies on the use of maltooligosaccharides in farm animal diets are considerably fewer. Therefore, their feed-related potential should be regarded as promising but not yet sufficiently validated. The most reasonable approach is to study maltooligosaccharides not as an already established independent feed technology, but as an additional starch-derived fraction within complex XOS–MalOS compositions obtained from wheat bran.

At the same time, existing data on the combined effects of XOS and maltooligosaccharides remain limited in both food and feed biotechnology. Most studies consider these oligosaccharides separately: XOS mainly as non-digestible xylan-derived prebiotics, and maltooligosaccharides as starch-derived fractions potentially capable of participating in microbial fermentation. Therefore, the hypothesis of a synergistic effect between XOS and maltooligosaccharides requires further experimental confirmation. Comparative studies evaluating individual XOS, individual maltooligosaccharides, and their combined compositions under identical digestion and fermentation conditions are especially important.

One of the key future directions is the standardization of oligosaccharide fraction composition. For XOS, it is necessary to consider the degree of polymerization, the proportion of xylobiose, xylotriose, and longer fractions, the level of arabinose substitution, and the presence of phenolic residues. For maltooligosaccharides, the distribution of DP fractions, the ratio of maltose, maltotriose, maltotetraose, and longer oligomers, as well as the presence of residual dextrins, are important. Without such standardization, it is difficult to correctly compare the results of different studies and assess the real contribution of each fraction to the prebiotic effect [18].

Another important direction is the optimization of enzymatic hydrolysis of wheat bran. Since the raw material contains both arabinoxylans and residual starch, the technological scheme must take into account the sequence of action of xylanolytic and amylolytic enzymes, pretreatment conditions, pH, temperature, hydrolysis duration, and enzyme-to-substrate ratio. A promising approach may involve stepwise processing: first, controlled treatment of the starch fraction to obtain maltooligosaccharides, followed by targeted hydrolysis of the arabinoxylan matrix to form XOS/AXOS. Alternatively, a combined enzyme system may be used; however, it requires strict control to avoid excessive monosaccharide formation and loss of the target oligosaccharide fractions.

Multilevel studies are required to confirm the functional efficacy of XOS–maltooligosaccharide compositions. At the first stage, *in vitro* models, including simulated digestion and fecal fermentation, should be used to assess fraction stability, growth dynamics of *Bifidobacterium* and *Lactobacillus*, pH changes, and short-chain fatty acid profiles. At the next stage, in vivo studies are needed, not only in laboratory animals but also in productive species such as poultry, pigs, and ruminants. For food applications, the final stage should involve clinical studies confirming safety, tolerability, effective dosage, and the actual effects of XOS–maltooligosaccharide compositions on human health [25, 44].

Thus, further development of this field should move from the general evaluation of wheat bran as a source of oligosaccharides toward the creation of standardized XOS–maltooligosaccharide fractions with defined structural and functional characteristics. The scientific and practical significance of this approach lies in the possibility of integrating deep processing technologies for cereal raw materials with the development of functional ingredients for the food industry and feed additives for animal husbandry. The potential value of such compositions is determined by their possible complementary effects on the gut microbiota, their ability to enhance short-chain fatty acid production, support the intestinal barrier, and their application in functional foods, nutraceuticals, specialized nutrition products, and prebiotic feed compositions.

Conclusion

Wheat bran represents a promising biopolymeric matrix for obtaining functional oligosaccharides, as it contains both an arabinoxylan fraction, which serves as a source of xylooligosaccharides (XOS),

and residual starch, which may be used as a source of maltooligosaccharides (MalOS). This combination allows wheat bran to be considered not only as a by-product of flour milling but also as a raw material for deep enzymatic processing aimed at producing value-added functional ingredients.

XOS and MalOS differ in their chemical structure, type of glycosidic linkages, and resistance to digestive enzymes, which determines differences in their fermentation kinetics and effects on the intestinal microbiota. XOS exhibit higher non-digestibility and may provide a more prolonged prebiotic effect, whereas MalOS may be incorporated into microbial fermentation more rapidly, provided that part of the fraction remains after digestion.

Thus, the available evidence supports the prebiotic effects of XOS, including their ability to modulate the gut microbiota and promote short-chain fatty acid production, with supporting data from animal studies. In contrast, the prebiotic potential of MalOS is supported mainly by *in vitro* evidence and requires further validation in productive animals. Therefore, the proposed complementary action of XOS and MalOS should currently be regarded as a scientifically grounded hypothesis rather than an experimentally confirmed synergistic effect. Further studies should focus on standardizing oligosaccharide fraction composition, optimizing enzymatic hydrolysis, and directly comparing XOS, MalOS, and their combinations using in vitro and in vivo models.

Author Contributions

Conceptualization: AK: formal analysis: AK, YS: resources: AK: writing-original draft preparation: AK, YS: writing-review and editing: AK, AK: funding acquisition: AK.

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Conflict of Interest

The authors declare that they have no known financial interests or personal relationships that could have influenced the results presented in this work.

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