Chapter 2
Prebiotics of Plant and Microbial Origin

Brittany M. Vester Boler and George C. Fahey Jr.

Abstract The food industry is constantly shifting focus based on what is most important to the consumer. Products are marketed currently that are believed to provide health benefits to the consumer such as beneficial effects on health or as disease preventatives. Much of the focus is on oligosaccharides as health-promoting substrates. Many oligosaccharides are resistant to digestion and absorption by mammalian enzymes and, therefore, reach the large bowel where they may be fermented by the resident bacteria. Beyond their potential as substrates for fermentation, oligosaccharides are popular food additives due in large part to their low caloric value and their ability to enhance mineral absorption. Health benefits include alleviation of constipation, reduced risk of infection and diarrhea, and improved immune response. Many oligosaccharides modulate microbiota of the large bowel by increasing bifidobacteria and lactobacilli populations and decreasing clostridia populations. This review will describe the manufacturing processes for select non-digestible oligosaccharides and other food ingredients currently classified as prebiotics and those with prebiotic potential.

2.1 Introduction

The food industry is constantly shifting focus based on what is most important to the consumer. Products are marketed currently that are believed to provide health benefits to the consumer. They are touted as either having beneficial effects on health or as disease preventatives. Because of the increased demand for these types of product, there is a growing interest in this research area that not only helps food

B.M.V. Boler • G.C. Fahey Jr. (✉)
Department of Animal Sciences, University of Illinois,
132 Animal Sciences Laboratory, Urbana, IL, USA
e-mail: gcfahey@illinois.edu

T.R. Callaway and S.C. Ricke (eds.), *Direct-Fed Microbials and Prebiotics for Animals: Science and Mechanisms of Action*, DOI 10.1007/978-1-4614-1311-0_2,

companies make accurate claims on products but helps identify new products that may lead to enhanced health.

Much of the focus is on oligosaccharides as health-promoting substrates. Oligosaccharides are low-molecular-weight carbohydrates with a low degree of polymerization (DP). They are either 2–20 monosaccharide units or no more than 10 monosaccharide units, depending on the official definition used (IUP-IUPAC 1982; Food and Drug Administration 1993). Many oligosaccharides are resistant to digestion and absorption by mammalian enzymes; and they therefore reach the large bowel, where they may be fermented by the resident bacteria. These oligosaccharides cannot be digested because the anomeric carbon atom has a configuration making the osidic bond resistant to mammalian enzymes. These oligosaccharides are termed "nondigestible oligosaccharides" (NDO).

Beyond their potential as substrates for fermentation, NDO are popular food additives due in large part to their low caloric value and their ability to enhance mineral absorption. NDO are water-soluble and sweet tasting; however, the sweetness decreases with increasing chain length. These products can aid in water binding and gelling, which can potentially decrease the amount of fat needed in a food product (Roberfroid and Slavin 2002). Health benefits linked to NDO ingestion include alleviation of constipation (Marteau 2001; Kaur and Gupta 2002), less risk of infection and diarrhea (Mussatto and Mancilha 2007), and improved immune response (Jenkins et al. 1999; Kelly-Quagliana et al. 2003; Manning and Gibson 2004). Other potential health benefits include modulation of lipid metabolism, reduced cancer risk, and treatment of hepatic encephalopathy (Swennen et al. 2006; Mussatto and Mancilha 2007). Many NDO also beneficially modulate microbiota of the large bowel by increasing bifidobacteria and lactobacilli populations and decreasing clostridial populations.

Select NDO have been classified as prebiotics. The concept of prebiotics was first introduced in 1995 (Gibson and Roberfroid 1995), and they have gained attention in industry and academia due to their potential health benefits. Prebiotics are defined as nondigestible food ingredients that are resistant to digestion and absorption (nondigestible), are fermented by cecal/colonic microbiota, and selectively stimulate growth and/or activity of bacteria that contribute to colonic and host health (Gibson et al. 2004; Roberfroid 2007). Only three NDO to date can be definitively classified as prebiotics: fructans, galactooligosaccharides (GOS), and lactulose. Although other NDO may have prebiotic potential, only limited research is available or the current data are conflicting, which does not allow them to be termed prebiotics. This review describes the manufacturing processes for select NDO and other food ingredients currently classified as prebiotics and those with prebiotic potential.

2.1.1 Methods of Manufacture

Nondigestible oligosaccharides have many uses in the food industry beyond use as a prebiotic. They have been used in food products to add bulk, reduce sweetness

Table 2.1 Definitions of some processing terms

Term	Definition
Hydrolysis	The cleaving of a molecule into two parts with the addition of a molecule of water
Extraction	Separation of compounds based on their solubility in two different liquids (usually water and an organic solvent)
Isomerization	The transformation of one molecule into a different one with the same molecular formula, but with a different structure
Transglycosylation	The transfer of a sugar residue from one glycoside to another

when other flavors should predominate, mask the taste of artificial sweeteners, and improve the mouth feel owing to their viscosity properties (Crittenden and Playne 1996; Mussatto and Mancilha 2007). Just as important, NDO are generally classified as "generally recognized as safe" (GRAS) and can be added to products meant for human and animal consumption. These products are generally safe and lead to only transient side effects when consumed in large doses; however, what constitutes a large dose is person/animal-dependent. Side effects of fermentable NDO include severe flatulence, intestinal discomfort, and osmotic diarrhea (Pederson et al. 1997; Cummings et al. 2001; Marteau 2001; Juśkiewicz and Zduńczyk 2002).

There are three main manufacturing processes for NDO: direct extraction from plants; controlled enzymatic hydrolysis of high-DP polysaccharides to lower DP oligosaccharides; and enzymatic-catalyzed synthesis via microbial action on simple sugars (Grizard and Barthomeuf 1999; L'Hocine et al. 2000). These processes use various chemical reactions, defined in Table 2.1. Inulin and soybean oligosaccharides (raffinose and stachyose) are two examples of NDO that can be directly extracted from plant sources (chicory root and soybeans, respectively). Commercially produced inulin, however, also undergoes hydrolysis of longer-chain polysaccharides to create a final product. Another example of controlled hydrolysis includes production of xylooligosaccharides from xylan. Finally, others are built using transglycosylation reactions with simple sugars such as the production of lactulose (Prenosil et al. 1987; Nilsson 1988; Okazaki et al. 1990; Playne 1994; Crittenden and Playne 1996).

2.1.2 Manufacture of Established Prebiotics

Fructans include inulin-type and levan-type oligosaccharides. Inulin-type fructans have β-2,1-D-fructofuranosyl units, are found in plants and synthesized by fungi, and have a DP of 2–70. Levan-type fructans have β-6,2-D-fructofuranosyl units, are found in plants and synthesized by bacteria, and have a DP > 30. Fructans occur naturally in plants such as chicory, Jerusalem artichoke, dahlia, salsify, gobo, onion, garlic, leek, and wheat by-products; and they serve as an energy source for these plants. Only inulin-type fructans are proven prebiotics (Roberfroid et al. 1998).

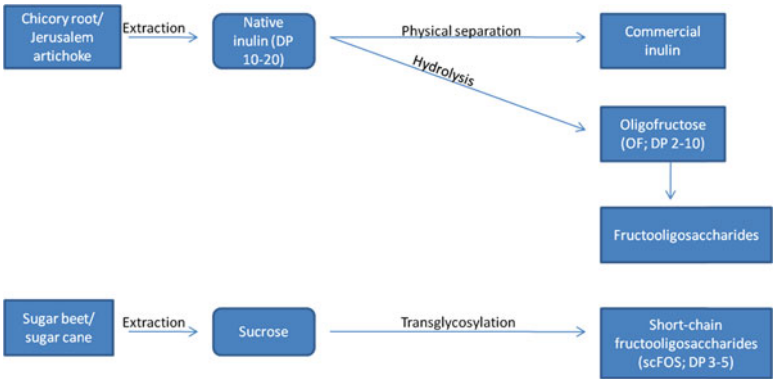

Fig. 2.1 Commercial production of inulin-type fructans from extracts of natural sources, partial enzymatic hydrolysis, or enzymatic synthesis from sucrose. *DP* degree of polymerization

Inulin is manufactured through direct hot water extraction from natural sources, mainly chicory root (Debruyn et al. 1992). It is composed of β(2-1) linkages of glucose and fructose [$G_{py}F_n$: α-D-glucopyranosyl-(β-D-fructofuranosyl)$_{n-1}$–D-fructofuranoside] or only fructose [$F_{py}F_n$: β-D-fructopyranosyl-(α-D-fructofuranosyl)$_{n-1}$–D-fructofuranoside] (Roberfroid and Delzenne 1998). Between 2 and 70 units of fructose may be present in native inulin, and it has an average DP of 10–20. Inulin comprises 15–20% of chicory root fresh weight with 55% of oligosaccharides with a DP of 2–19, 28% with a DP of 20–40, and 17% with a DP of >40. It comprises 17–20% of Jerusalem artichoke fresh weight with 74% of oligosaccharides with a DP of 2–19, 20% with a DP of 20–40, and 6% with a DP of >40 (Van Loo et al. 1995).

After extraction of native inulin, the product then undergoes either industrial physical separation of long-chain fructans (De Leenheer 1996) or is partially hydrolyzed by endoinulinase to produce short-chain oligosaccharides, mainly oligofructose (Fig. 2.1). Oligofructose produced from inulin may or may not have a terminating glucose molecule, may contain longer-chain fructans (Crittenden and Playne 1996), and has a DP of 2–10 (average 5) (Roberfroid and Delzenne 1998). Alternatively, short-chain fructooligosaccharides can be produced synthetically through transfructosylation of sucrose using the β-fructofuranosidase enzyme (Crittenden and Playne 1996) from *Aureobasidium pullulans* (Yun 1996; Yoshhikawa et al. 2008) or *Aspergillus niger* (Park and Almeida 1991). These compounds contain 2–4 fructosyl units with a terminal glucose unit and an average DP of 3.5 (Roberfroid and Delzenne 1996). Synthetic fructooligosaccharides contain only $G_{py}F_n$ oligomers. These products may contain free glucose, fructose, and sucrose, which can be removed via chromatographic procedures to increase the purity of the final product. It should be noted, however, that a large amount of starting material is needed to achieve efficient transglycosylation (Park and Almeida 1991).

Fructans are perhaps the most well-established prebiotics (Roberfroid 2007) and the most extensively studied. They meet the three key criteria defining a prebiotic,

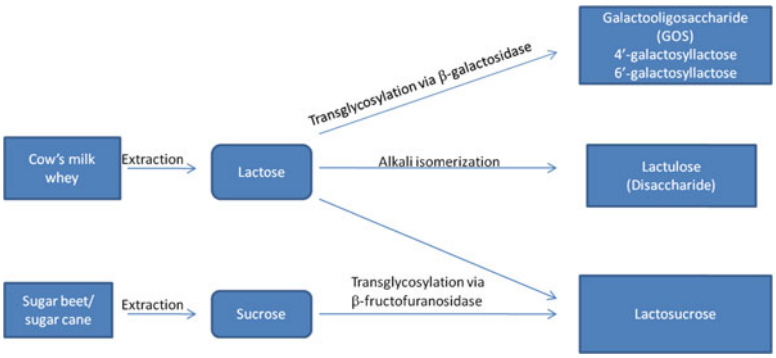

Fig. 2.2 Commerical production of lactose-derived prebiotics via transglycosylation to produce galactooligosaccharides, alkali isomerization to produce lactulose, or transglycosylation with sucrose to produce lactosucrose

that inulin-type fructans are nondigestible (Cherbut 2002), are fermented in the large bowel, and lead to selective growth of bacteria associated with health in vitro (Roberfroid et al. 1998) and in vivo [human subjects, including infants (Coppa et al. 2002), adults (Harmsen et al. 1999), and the elderly (Guigoz et al. 2002)].

Galactooligosaccharides are produced from lactose (Fig. 2.2) and are defined as oligosaccharides with 2–8 galactose or disaccharide units (two units of galactose) with a terminal glucose. Commercial production utilizes highly concentrated lactose from cow milk whey. Lactose undergoes transglycosylation from β-galactosidase enzymes (the glycosyltransferases and glycohydrolases). The types of GOS produced depend on the type of β-galactosidases used and the processing conditions (Mussatto and Mancilha 2007).

Galactosyltransferases move a sugar unit from the donor to the receptor molecule, forming a glycosidic bond (Tzortis and Vulevic 2009). Although production of GOS is relatively efficient, galactosyltransferase enzymes are difficult to find; and the need for sugar nucleotides in the reaction makes them cost-prohibitive to the industry. Galactohydrase enzymes are more readily available but lack the specificity of galactosyltransferases. Microbial stains used for enzyme production include *A. oryzae* and/or *Strep. thermophilus*, which form β-1,6 bonds, or *Bacillus circulans* or *Cryptococcus laurentii*, which form β-1,4 bonds (Sako et al. 1999).

Approximately 55% of the starting lactose is converted to GOS. These GOS produced are mostly trisaccharides (4′-galactosyllactose and 6′-galactosyllactose) that have 2–5 galactose units and longer-chain oligosaccharides with four or more monosaccharide units. Generally, 80% of the oligosaccharides formed are trisaccharides (Playne and Crittenden 2004). Other products present at the end of the reaction include lactose, galactose, and glucose disaccharides and transgalactosylated disaccharides (Sako et al. 1999). These transgalactosylated disaccharides produced are considered NDO as they have properties similar to those of longer-chain GOS.

Commercial GOS products are generally made in batch systems for simplicity; however, this method is the least efficient, and most of the enzyme added to the initial reaction is lost. Continuous systems have been proposed to cut production costs by using ultrafiltration to retain soluble enzymes via enzyme immobilization (Tzortis and Vulevic 2009). During batch reactions, multiple enzymes may be added at the initial reaction or in sequence during the reaction. The mixture is heated to facilitate lactose solubilization and drive the formation of oligosaccharides over hydrolysis of lactose to monosaccharides (Playne and Crittenden 2004). Unreacted products may be removed using chromatography, although lactose has been noted to be difficult to remove and leads to a loss of GOS. Furthermore, the product is decolorized, demineralized, and concentrated to a syrup or powder form. A highly consistent product can be developed by maintaining strict production conditions, although all final products are mixtures of various GOS products (Playne and Crittenden 2004).

Although there is no overwhelming evidence of its prebiotic potential, as is the case with fructans, GOS are considered to be a proven prebiotic (Roberfroid 2007). Evidence, though minimal, suggests that GOS are not hydrolyzed by mammalian enzymes (Tanaka et al. 1983). It has been established that selective bacterial stimulation occurs, however, as increases in bifidobacteria and lactobacilli have been noted in several studies (Ito et al. 1990; Bouhnik et al. 1997; Moro et al. 2002). Therefore, although it is probable that GOS are not digested by mammalian enzymes and it has been proven that they lead to selective growth of beneficial bacteria, few data are available on their fermentation potential in the large bowel (Roberfroid 2007).

Lactulose, like GOS, is produced from lactose (Fig. 2.2). It is formed through alkali isomerization of the glucose moiety of lactose to fructose, thereby making it a combination of fructose and galactose. The resulting disaccharides with β-1,4 linkages are not digested by mammalian enzymes. To manufacture lactulose, lactose is mixed with an alkali (e.g., sodium hydroxide), and a catalyst may be added (Playne and Crittenden 2004). The mixture then is heated to facilitate isomerization. The unreacted lactose is removed, and the product is pasteurized and then concentrated into syrups, powders, or crystals.

Commercial lactulose is expensive to produce, as only 20–30% of lactose is converted after isomerization, and expensive purification techniques are required. Lactulose is known to have prebiotic effects and may be used in that capacity or as a low-calorie sweetener. Most lactulose (90%), however, is used pharmaceutically to prevent constipation and in patients with hepatic encephalopathy to reduce blood ammonia concentrations (Crittenden and Playne 1996).

Despite the fact that lactulose is classified as a proven prebiotic because of its extensive published human database, its use as a food supplement is limited (Roberfroid 2008). This is probably because lactulose is resistant to mammalian enzymes (Gibson and Angus 2008), although research on the subject is limited. Key animal and human studies indicate that it is fermented in the large bowel, and it has the ability selectively to stimulate bifidobacteria and lactobacilli populations (Terada et al. 1993; Ballongue et al. 1997; Tuohy et al. 2002). Therefore, although further research would help clarify its status, lactulose is considered a proven prebiotic (Roberfroid 2007, 2008).

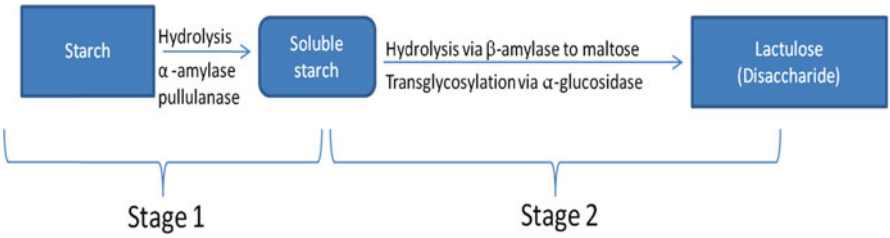

Fig. 2.3 Commercial production of lactulose, a two-stage process. The first stage hydrolyzes starch to a liquefied product. During the second phase, soluble starch undergoes transglycosylation to lactulose

2.1.3 Manufacture of Promising Prebiotics

Isomaltooligosaccharides (IMO) consist of glucose monomers with α-1,6 glucosidic bonds (Fig. 2.3). Although the food industry uses commercially produced material, IMO occur naturally in miso, soy sauce, sake, and honey. Commercial production of IMO is a two-stage process, with starch as the starting material. Starch is first hydrolyzed with α-amylase and pullulanase to make a liquefied starch product. β-Amylase hydrolyzes the liquefied starch to maltose, and then the transglucosidase activity of α-glucosidase produces IMO with a maximum final concentration of 40% of the total mixture (Casci and Rastall 2006). Unreacted glucose (approximately 40% of the final mixture) is then removed, and the product is concentrated. Although in vitro and cell culture data indicate that IMO have potential as prebiotics, to date limited data are available to classify it as such.

Lactosucrose is a trisaccharide produced from lactose and sucrose in a reversible reaction (Fig. 2.2). The fructosyl moiety of sucrose forms a β-2,1 glycosidic bond to the glucose residue of lactose to create lactosucrose. This is done by transglycosylation via a β-fructofuranosidase enzyme, which produces a nonreducing oligosaccharide (Hara et al. 1994). This enzyme, however, also can hydrolyze sucrose (Mussatto and Mancilha 2007). Therefore, in a batch system, with an initial equimolar ratio, there is a yield of only 52% lactosucrose (Kawase et al. 2001). Cleanup of this product is complicated and includes decolorization, filtration, concentration, purification, filtration, deionization, and, again, concentration (Playne and Crittenden 2004). Although lactosucrose has been noted to be bifidogenic in small human trials (Kumemura 1992; Ohkusa et al. 1995), the data regarding its bifidogenic capabilities are limited. Moreover, there are no data available on its ability to withstand hydrolysis in the gastrointestinal tract (Roberfroid 2008).

Xylooligosaccharides (XOS) consist of chains of xylose molecules with β-1,4 linkages. It is a naturally occurring oligosaccharide found in honey, bamboo shoots, fruits, vegetables, and milk (Vázquez et al. 2000). It also can be made by breaking down the polysaccharide, xylan, a major component of hemicelluloses, into XOS. Commercial production is conducted through enzymatic hydrolysis of primarily corncobs but also straws, hardwoods, bagasse, hulls, and bran using endo-1,4-β-xylanase

Fig. 2.4 Commercial production of xylooligosaccharides, which are most commonly from corncobs but also can be extracted from hardwood. Xylooligosaccharides are extracted by hydrolyzing xylans in the starting material using endo-1,4-β-xylanase

(Fig. 2.4). Using enzymes with low exoxylanase and/or β-xylosidase activity is prudent to minimize production of xylose. Xylanases are produced by *Trichoderma reesei*, *T. harzianum*, *T. viride*, *T. koningii*, and *T. longibrachiatum* (Chen et al. 1997; Casci and Rastall 2006). Other methods for extracting XOSs include (1) chemical fractionation of material to isolate xylan with further enzymatic hydrolysis and (2) hydrolytic degradation of xylan by steam, water, or dilute mineral acid solutions (Vázquez et al. 2000). Chains produced through extraction in all processes include xylobiose, xylotriose, and xylotetraose (Hopkins et al. 1998).

Prior to cleaning, the solution contains approximately 60–70% XOS (Playne and Crittenden 2004). After production, xylose and other compounds are removed with ultrapurification and reverse osmosis (Crittenden and Playne1996) to create a product generally containing 70% or 95% oligosaccharides (Xylooligo 70 and Xylooligo 95, respectively) (Playne and Crittenden 2004). Data indicate that XOS are bifidogenic (Okazaki et al. 1990; Campbell et al. 1997). It is likely that they are resistant to hydrolytic digestion because xylan is a dietary fiber, but there are no data to support this assumption. Therefore, XOS cannot currently be classified as a prebiotic (Roberfroid 2008).

2.1.4 Manufacture of Potential Prebiotics

In addition to the previously described NDO that are considered prebiotics or potential prebiotics, there are several others that have not yet met the burden of proof to be classified as prebiotics. This is most commonly due to the limited research on these compounds. Alternatively, the limited data that do exist may show conflicting results, and some researchers have not evaluated changes in the microbiota. Beyond oligosaccharides, some longer-chain carbohydrate sources may also have prebiotic capabilities. Those potential prebiotic carbohydrates are listed in Table 2.2. There are even noncarbohydrate food ingredients that have potential to be classified as prebiotics, including lactoferrin, phenolic compounds (e.g., flavonoids), and glutamine. To date, however, little research has been done on any of those compounds.

Interestingly, polysaccharides with prebiotic potential may be more beneficial than some NDO prebiotics. This is due to the fact that polysaccharides can be consumed in higher doses without adverse side effects, such as intestinal discomfort

Table 2.2 Potential prebiotic carbohydrates

• Soybean oligosaccharides	• Mannanoligosaccharides (yeast cell wall)
• Glucooligosaccharides	• Lactose
• Cyclodextrins	• Resistant starch and derivatives
• Gentiooligosaccharides	• Oligosaccharides from melobiose
• Germinated barley foodstuffs	• N-acetylchitooligosaccharides
• Oligodextrans	• Polydextrose
• Glucuronic acid	• Sugar alcohols
• Gentiooligosaccharides	• Konjac glucomannan
• Pectic oligosaccharides	• Whole grains

and excessive flatulence (Crittenden 2006). Polysaccharides also have the potential of being fermented throughout the length of the colon, including the distal colon, the major site of large bowel disease. Potential prebiotics of interest include resistant starch, whole grains, and polydextrose.

Not all dietary starch is hydrolyzed and absorbed, as some starch is resistant to enzymatic hydrolysis. This fraction is termed resistant starch. How much starch reaches the large bowel and if it can be fermented depend on its source and structure. Resistant starch is classified in one of four ways (1) RS1, which is physically inaccessible starch (e.g., starch in whole grains); (2) RS2, which is granular starch (e.g., starch in green bananas or uncooked potatoes); (3) RS3, which is retrograded starch (e.g., starch in cooked, then cooled, potatoes); or (4) chemically modified starch (e.g., esterified starch) (Brown 1996).

Research on the prebiotic effects of resistant starch has focused on RS2 and RS3. Although research is lacking overall, RS2 and RS3 have been noted to have prebiotic capabilities in animals and animal models (Brown et al. 1997; Silvi et al. 1999; Wang et al. 2002; Dongowski et al. 2005; Jabocasch et al. 2006) and humans (Bouhnik et al. 2004). Resistant starch has been noted in several studies to increase bifidobacteria and/or lactobacilli populations (Kleessen et al. 1997; Silvi et al. 1999; Wang et al. 2002; Dongowski et al. 2005; Jabocasch et al. 2006) and to increase short-chain fatty acids, especially butyrate (Brown et al. 1997). Not all studies, however, report a bifidogenic response by resistant starches (Bird et al. 2004). Although it is evident that resistant starch is not digested by mammalian enzymes and can be fermented, the largest question remaining as to its prebiotic potential is its selectivity, as many other bacterial species are amylolytic, and many of the health benefits of resistant starch can be attributed to the production of butyrate (Crittenden 2006).

Polysaccharides are beginning to receive more attention as potential prebiotics. Furthermore, the use of whole grains in the food industry has increased markedly. Whole grains themselves have been investigated, as well as oligosaccharides that can be obtained through breakdown of polysaccharides by glyconases (Mussatto and Mancilha 2007). Limited research indicates these oligosaccharides have prebiotic potential (Rastall and Maitin 2002).

The best studied whole grain components include β-glucans and arabinoxylan oligosaccharides, which are fermented in the gastrointestinal tract (Fleming et al. 1983; Fincher and Stone 1986). In vitro studies indicate that β-glucans are not well

fermented by bifidobacteria and lactobacilli (Crittenden et al. 2002). Arabinoxylan, however, may have a bifidogenic effect and may be of particular use as it is more slowly fermented than inulin (Karppinen et al. 2000).

Whole grains have limited fermentation potential in vitro, but after processing the substrates produce greater quantities of total short-chain fatty acids (Hernot et al. 2008); however, bacterial population changes were not reported in that study. In vivo, whole grains resulted in greater *Bifidobacterium* spp. and lactobacilli concentrations in healthy adults after consuming wheat bran as a wheat bran-based breakfast cereal or whole grain as a 100% whole grain wheat cereal. This effect was greater with whole grains (Constabile et al. 2008). It is clear that whole grains and their components have potential prebiotic effects, but more research is needed regarding their fermentative capabilities and bacterial selectivity.

Polydextrose is a polysaccharide formed through acid-catalyzed vacuum thermal polymerization of glucose and sorbitol that has an average DP of 12 but can be as high as 30 (Stowell 2009; Li 2010). It is a highly branched compound, with β-1,6 linkages predominating. Polydextrose currently is used to replace fat and sucrose in food products, as a humectant, and to provide mouth feel and bulk to food products (Murphy 2001). It is well documented that it resists enzymatic hydrolysis by mammalian enzymes (Figdor and Rennhard 1981; Achour et al. 1994; Fava et al. 2007). Animal and human studies report that approximately 30–50% of polydextrose is fermented in the large bowel (Figdor and Rennhard 1981; Achour et al. 1994).

In vitro studies indicate that polydextrose enhances butyrate and other short-chain fatty acid production (Stowell 2010). There is emerging evidence that polydextrose leads to selective increases in beneficial bacteria. Jie et al. (2000) reported increased *Bifidobacterium* and *Lactobacillus* spp. in healthy adult humans, and Tiihonen et al. (2008) noted greater bifidobacteria species in healthy adults fed polydextrose plus a probiotic compared with the probiotic alone. Therefore, polydextrose likely has prebiotic capabilities, but more research is needed to determine conclusively if this is the case.

2.2 Conclusions

There are three carbohydrates proven to meet all requirements of the prebiotic definition: inulin-type fructans, GOS, and lactulose. All three prebiotics are manufactured in a unique manner but have a common characteristic in that all need a large amount of starting substrate to produce the end-product. Relatively consistent final products for use by humans and animals result from the manufacturing process.

Several other NDO show promising results in the limited research available regarding their prebiotic potential. Some prebiotics with promising results include IMO, lactosucrose, and XOS. Finally, there are even more carbohydrate and noncarbohydrate food ingredients that may have prebiotic effects when fed to animals and humans. More research defining their prebiotic potential is needed.

References

Achour, L., B. Flourie, F. Briet, et al. 1994. Gastro-intestinal effects and energy value of polydextrose in healthy non-obese men. *American Journal of Clinical Nutrition* 59: 1362–1368.

Ballongue, J., C. Schumann, and P. Quignon. 1997. Effects of lactulose and lactitol on colonic microflora and enzymatic activity. *Scandinavian Journal of Gastroenterology* 222: 41–44.

Bird, A.R., M. Jackson, R.A. King, et al. 2004. A novel high-amylose barley cultivar (*Hordeum vulgare* var. Himalaya 292) lowers plasma cholesterol and alters indices of large-bowel fermentation in pigs. *British Journal of Nutrition* 92: 607–615.

Bouhnik, Y., B. Flourié, L. D'Agay-Abensour, et al. 1997. Administration of transgalactooligosaccharides increases fecal bifidobacteria and modifies colonic fermentation metabolism in healthy humans. *Journal of Nutrition* 127: 444–448.

Bouhnik, Y., L. Raskine, G. Simoneau, et al. 2004. The capacity of nondigestible carbohydrates to stimulate fecal bifidobacteria in healthy humans: A double-blind, randomized, placebo-controlled, parallel group, dose–response relation study. *American Journal of Clinical Nutrition* 80: 1658–1664.

Brown, I. 1996. Complex carbohydrates and resistant starch. *Nutrition Reviews* 54: 3115–3119.

Brown, I., M. Warhurst, J. Arcot, et al. 1997. Fecal numbers of bifidobacteria are higher in pigs fed *Bifidobacterium longum* with high amylose cornstarch than with low amylose cornstarch. *Journal of Nutrition* 127: 1822–1827.

Campbell, J.M., G.C. Fahey Jr., and B.W. Wolf. 1997. Selected indigestible oligosaccharides affect large bowel mass, cecal and fecal short-chain fatty acids, pH, and microflora in rats. *Journal of Nutrition* 127: 130–136.

Casci, T., and R.A. Rastall. 2006. Manufacture of prebiotic oligosaccharides. In *Prebiotics: Development and application*, ed. G.R. Gibson and R.A. Rastall. West Sussex, UK: Wiley.

Chen, C., J.-L. Chen, and T.-Y. Lin. 1997. Purification and characterization of a xylanase from *Trichoderma longibrachiatum* for xylooligosaccharide production. *Enzyme and Microbial Technology* 21: 91–96.

Cherbut C (2002) Inulin and oligofructose in the dietary fibre concept. *British Journal of Nutrition* 87, Suppl. 2: S159–S162.

Constabile, A., A. Klinder, F. Fava, et al. 2008. Whole-grain wheat breakfast cereal has a prebiotic effect on the human gut microbiota: A double-blind, placebo-controlled, crossover study. *British Journal of Nutrition* 99: 110–120.

Coppa, G.V., S. Bruni, and L. Zampini. 2002. Prebiotics in infant formulas: Biochemical characterization by thin layer chromatography and high performance anion exchange chromatography. *Digestive and Liver Disease* 34: S124–S128.

Crittenden, R.G. 2006. Emerging prebiotic candidates. In *Prebiotics: Development and application*, ed. G.R. Gibson and R.A. Rastall. West Sussex: Wiley.

Crittenden, R.G., and M.J. Playne. 1996. Production, properties and applications of food-grade oligosaccharides. *Trends in Food Science and Technology* 7: 353–361.

Crittenden, R.G., S. Karppinen, S. Ojanen, et al. 2002. In vitro fermentation of cereal dietary fiber carbohydrates by probiotic and intestinal bacteria. *Journal of the Science of Food and Agriculture* 82: 1–9.

Cummings, J.H., G.T. Macfarlane, and H.N. Englyst. 2001. Prebiotic digestion and fermentation. *American Journal of Clinical Nutrition* 73: 415S–420S.

De Leenheer, L. 1996. Production and use of inulin: Industrial reality with a promising future. In *Carbohydrates as organic raw materials*, vol. III, ed. H. Van Bekkun, H. Röper, and H. Vorgen. Weinheim: Wiley-VCH.

Debruyn, A., A.P. Alvarez, P. Sandra, et al. 1992. Isolation and identification of O-β-D-fructofuranosyl-(2 → 1)-O-β-D-fructofuranosyl-(2 → 1)-D-fructose, a product of the enzymatic hydrolysis of the inulin from *Cichorium intybus*. *Carbohydrate Research* 235: 303–308.

Dongowski, G., G. Jacobasch, and D. Schmiedl. 2005. Structural stability and prebiotic properties of resistant starch type 3 increase bile acid turnover and lower secondary bile acid formation. *Journal of Agricultural and Food Chemistry* 53: 9257–9267.

Fava, F., H. Mäkivuokko, H. Siljander-Rasi, et al. 2007. Effect of polydextrose and intestinal microbes and immune functions in pigs. *British Journal of Nutrition* 98: 123–133.

Figdor, S.K., and H.H. Rennhard. 1981. Caloric utilization and disposition of [^{14}C] polydextrose in the rat. *Journal of Agricultural and Food Chemistry* 29: 1181–1189.

Fincher, G.B., and B.A. Stone. 1986. Cell walls and their components in cereal grain technology. *Advances in Cereal Science and Technology* 6: 207–295.

Fleming, S.E., D. Marthinsen, and H. Kuhnlein. 1983. Colonic function and fermentation in men consuming high fiber diets. *Journal of Nutrition* 113: 2535–2544.

Food and Drug Administration. 1993. Food labeling: Mandatory status of nutrition labeling and nutrient content revision, format for nutrition label. *Federal Register* 58: 2079.

Gibson, G.R., and F. Angus. 2000. Leatherhead Ingredients Handbook: Prebiotics and Probiotics. Leatherhead, UK: Leatherhead Food Research Association.

Gibson, G.R., and M.B. Roberfroid. 1995. Dietary modulation of the human colonic microbiota: Introducing the concept of prebiotics. *Journal of Nutrition* 125: 1401–1412.

Gibson, G.R., H.M. Probert, J. Van Loo, R.A. Rastall, and M.B. Roberfroid. 2004. Dietary modulation of the human colonic microbiota: Updating the concept of prebiotics. *Nutrition Research Reviews* 17: 259–275.

Grizard, D., and C. Barthomeuf. 1999. Non-digestible oligosaccharides used as prebiotic agents: Mode of production and beneficial effects on animal and human health. *Reproduction Nutrition Development* 39: 563–588.

Guigoz, Y., F. Rochat, and G. Prerruisseau-Carrier. 2002. Effects of oligosaccharide on the faecal flora and non-specific immune system in elderly people. *Nutrition Research* 22: 13–25.

Hara, H., S. Li, M. Sasaki, et al. 1994. Effective dose of lactosucrose on fecal flora and fecal metabolites of humans. *Bifidobacteria Microflora* 13: 51–63.

Harmsen, H.J.M., P. Elfferich, F. Schut, et al. 1999. A 16S rRNA-targeted probe for detection of lactobacilli and enterocci in faecal samples by fluorescent in situ hybridization. *Microbial Ecology in Health and Disease* 11: 3–12.

Hernot, D.C., T.W. Boileau, L.L. Bauer, et al. 2008. In vitro digestion characteristics of unprocessed and processed whole grains and their components. *Journal of Agricultural and Food Chemistry* 56: 10721–10726.

Hopkins, M., J. Cummings, and G. MacFarlane. 1998. Inter-species differences in maximum specific growth rates and cell yields of bifidobacteria cultured on oligosaccharides and other simple carbohydrate sources. *Journal of Applied Microbiology* 85: 381–386.

Ito, M., Y. Deguchi, A. Miyamori, et al. 1990. Effect of administration of galacto-oligosaccarides on the human faecal flora, stool weight and abdominal sensation. *Microbial Ecology in Health and Disease* 3: 285–292.

IUP-IUPAC. 1982. Joint commission on biochemical nomenclature and (JCBN): Abbreviated terminology of oligosaccharide chains: Recommendations 1980. *Journal of Biological Chemistry* 257: 3347–3351.

Jabocasch, G., G. Dongowski, D. Schmiedl, et al. 2006. Hydrothermal treatment of Novelose 330 results in high yield of resistant starch type 3 with beneficial prebiotic properties and decreased secondary bile acid formation in rats. *British Journal of Nutrition* 95: 1063–1074.

Jenkins, D.J.A., C.W.C. Kendall, and V. Vuksan. 1999. Inulin, oligofructose and intestinal function. *Journal of Nutrition* 129: 1431S–1433S.

Jie, Z., B. Lou, M. Xiang, et al. 2000. Studies on the effects of polydextrose on physiological function in Chinese people. *American Journal of Clinical Nutrition* 72: 1503–1509.

Juśkiewicz, J., and Z. Zduńczyk. 2002. Lactulose-induced diarrhoea in rats: Effects on caecal development and activities of microbial enzymes. *Comparative Biochemistry and Physiology* 133: 411–417.

Karppinen, S., K. Liukkonen, A.M. Aura, et al. 2000. In vitro fermentation of polysaccharides of rye, wheat and oat brans and inulin by human faecal bacteria. *Journal of the Science of Food and Agriculture* 80: 1469–1476.

Kaur, N., and A. Gupta. 2002. Applications of inulin and oligofructose in health and nutrition. *Journal of Biosciences* 27: 703–714.

Kawase, M., A. Pilgrim, T. Araki, et al. 2001. Lactosucrose production using a simulated moving bed reactor. *Chemical Engineering Science* 56: 453–458.

Kelly-Quagliana, K.A., P.D. Nelson, and R.K. Buddington. 2003. Dietary oligofructose and inulin modulate immune functions in mice. *Nutrition Research* 23: 257–267.

Kleessen, B., G. Stoof, J. Proll, et al. 1997. Feeding resistant starch affects fecal and cecal microflora and short chain fatty acids in rats. *Journal of Animal Science* 75: 2453–2462.

Kumemura, M. 1992. Effects of administration of 4G-β-D-galactosylsucrose on fecal microflora putrefactive compounds, short chain fatty acids, weight, moisture, and subjective sensation of defecation in the elderly constipation. *Journal of Clinical Biochemistry and Nutrition* 13: 199–210.

L'Hocine, L., Z. Wang, G. Jian, and S.Y. Xu. 2000. Purification and partial characterization of fructosyltransferase and invertase from *Aspergillus niger* AS0023. *Journal of Biotechnology* 81: 73–84.

Li, B.W. 2010. Analysis of dietary fiber and nondigestible carbohydrates. In *Handbook of prebiotics and probiotics ingredients: Health benefits and food applications*, ed. S.S. Cho and E.T. Finocchiara. Boca Raton, FL: CRC Press.

Manning, T.S., and G.R. Gibson. 2004. Prebiotics. *Best Practice and Research Clinical Gasteroenterology* 108: 975–982.

Marteau, P. 2001. Prebiotics and probiotics for gastrointestinal health. *Clinical Nutrition* 40: 41–45.

Moro, G., I. Minoli, M. Mosca, et al. 2002. Dosage-related bifidogenic effects of galacto- and fructoligosaccharides in formula-fed term infants. *Journal of Pediatrics Gastroenterology and Nutrition* 34: 291–295.

Murphy, O. 2001. Non-polyol low-digestible carbohydrates: Food application and functional benefits. *British Journal of Nutrition* 85: S47–S53.

Mussatto, S.I., and I.M. Mancilha. 2007. Non-digestible oligosaccharides: A review. *Carbohydrate Polymers* 68: 587–597.

Nilsson, K.G.I. 1988. Enzymatic synthesis of oligosaccharides. *Trends in Biotechnology* 6: 256–264.

Ohkusa, T., Y. Ozaki, C. Sato, et al. 1995. Long-term ingestion of lactosucrose increases *Bifidobacterium* spp. in human fecal flora. *Digestion* 56: 415–420.

Okazaki, M., S. Fujikawa, and N. Mutumoto. 1990. Effect of xylooligosaccharide on the growth of bifidobacteria. *Bifidobacteria Microflora* 9: 77–86.

Park, Y.K., and M.M. Almeida. 1991. Production of fructooligosaccharides from sucrose by tranfructosylase from *Aspergillus niger*. *World Journal of Microbiology and Biotechnology* 7: 331–334.

Pederson, A., B. Sanstrom, and J.M.M. van Amelsvoort. 1997. The effect of ingestion of inulin on blood lipids and gastrointestinal symptoms in healthy females. *British Journal of Nutrition* 78: 215–222.

Playne, M.J. 1994. Production of carbohydrate-based functional foods using enzyme and fermentation technologies. *Int Chem Eng Symp Ser* 137: 147–156.

Playne, M.J., and R.G. Crittenden. 2004. Prebiotics from lactose, sucrose, starch, and plant polysaccharides. In *Bioprocesses and biotechnology for functional foods and nutraceuticals*, ed. J.-R. Neeser and J.B. German. New York: Marcel Dekker.

Prenosil, J.E., E. Stucker, and J.R. Bourne. 1987. Formation of oligosaccharides during enzymatic lactose. Part 1: State of art. *Biotechnology and Bioengineering* 30: 1019–1025.

Rastall, R.A., and V. Maitin. 2002. Prebiotics and synbiotics: Towards the next generation. *Current Opinion Biotechnology* 13: 490–496.

Roberfroid, M.B., and J. Slavin. 2000. Nondigestible oligosaccharides.Critical Review in Food Science and Nutrition 40: 461–480.

Roberfroid, M.B., and N. Delzenne. 1998. Dietary fructans. Annual Review Nutrition 18: 117–143.

Roberfroid, M.B. 2007. Prebiotics: The concept revisited. *Journal of Nutrition* 137: 830S–837S.

Roberfroid, M.B. 2008. Prebiotics: Concepts, definition, criteria, methodologies, and products. In *Handbook of prebiotics*, ed. G.R. Gibson and M.B. Roberfroid. Boca Raton: CRC Press.

Roberfroid, M.B., and N.M. Delzenne. 1998. Dietary fructans. *Annual Review of Nutrition* 18: 117–143.

Roberfroid, M.B., J.A.E. Van Loo, and G.R. Gibson. 1998. The bifidogenic nature of chicory inulin and its hydrolysis products. *Journal of Nutrition* 128: 11–19.

Sako, T., K. Mastumoto, and R. Tanaka. 1999. Recent progress on research and applications of non-digestible galacto-oligosaccharides. *International Dairy Journal* 9: 69–80.

Silvi, S., C.J. Rumney, A. Cresci, et al. 1999. Resistant starch modifies gut microflora and microbial metabolism in human flora-associated rats inoculated with feces from Italian and UK donors. *Journal of Applied Microbiology* 86: 521–530.

Stowell, J.D. 2009. Polydextrose. In *Fiber ingredients: Food applications and health benefits*, ed. S.S. Cho and P. Samuel. Boca Raton: CRC Press.

Stowell, J.D. 2010. Prebiotic potential of polydextrose. In *Prebiotics and probiotics science and technology*, ed. D. Charalampopoulos and R.A. Rastall. New York: Springer.

Swennen, K., C.M. Courtin, and J.A. Delcour. 2006. Non-digestible oligosaccharides with prebiotic properties. *Critical Reviews in Food Science and Nutrition* 46: 459–471.

Tanaka, R., H. Takayama, M. Morotomi, et al. 1983. Effects of administration of TOS and *Bifidobacterium breve* 4006 on the human fecal flora. *Bifidobacteria Microflora* 2: 17–24.

Terada, A., H. Hara, S. Kato, et al. 1993. Effect of lactosucrose (4G-β-D-galactosylsucrose) on fecal flora and fecal putrefactive products of cats. *The Journal of Veterinary Medical Science* 55: 291–295.

Tiihonen, K., T. Suomalainen, S. Tynkknen, et al. 2008. Effect of prebiotic supplementation on a probiotic bacterial mixture: Comparison between a rat model and clinical trials. *British Journal of Nutrition* 99: 826–831.

Tuohy, K.M., C.J. Ziemer, A. Klinder, et al. 2002. A human volunteer study to determine the prebiotic effects of lactulose powder on human colonic microbiota. *Microbial Ecology in Health and Disease* 14: 165–173.

Tzortis, G., and J. Vulevic. 2009. Galacto-oligosaccharide prebiotics. In *Prebiotics and probiotics science and technology*, ed. D. Charalampopoulos and R.A. Rastall. New York: Springer.

Van Loo, J., P. Coussement, L. De Leenheer, et al. 1995. On the presence of inulin and oligofructose as natural ingredients in the Western diet. *Critical Reviews in Food Science and Nutrition* 35: 525–552.

Vázquez, M.J., J.L. Alonso, H. Domínguez, et al. 2000. Xylooligo-saccharides: Manufacture and applications. *Trends in Food Science and Technology* 11: 387–393.

Wang, X., I.L. Brown, D. Khaled, et al. 2002. Manipulation of colonic bacteria and volatile fatty acid production by dietary high amylose maize (amylomaize) starch granules. *Journal of Applied Microbiology* 93: 390–397.

Yoshhikawa, J., S. Amachi, H. Shinoyama, et al. 2008. Production of fructooligosaccharides by crude enzyme preparations of β-fructofuranosidase from *Aureobasidium pullulans*. *Biotechnology Letters* 30: 535–539.

Yun, J.W. 1996. Fructooligosaccharides: Occurrence, preparation, and application. *Enzyme and Microbial Technology* 19: 107–117.

http://www.springer.com/978-1-4614-1310-3

Direct-Fed Microbials and Prebiotics for Animals
Science and Mechanisms of Action
Callaway, T.R.; Ricke, S.C. (Eds.)
2012, XIV, 206 p., Hardcover
ISBN: 978-1-4614-1310-3