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Reaction kinetics and galactooligosaccharide product profiles of the β-galactosidases from *Bacillus circulans*, *Kluyveromyces lactis* and *Aspergillus oryzae*

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ABSTRACT

β-Galactosidase enzymes are used in the dairy industry to convert lactose into galactooligosaccharides (GOS) that are added to infant formula to mimic the molecular sizes and prebiotic functions of human milk oligosaccharides. Here we report a detailed analysis of the clearly different GOS profiles of the commercial β-galactosidases from *Bacillus circulans*, *Kluyveromyces lactis* and *Aspergillus oryzae*. Also the GOS yields of these enzymes differed, varying from 48.3% (*B. circulans*) to 34.9% (*K. lactis*), and 19.5% (*A. oryzae*). Their incubation with lactose plus the monosaccharides Gal or Glc resulted in altered GOS profiles. Experiments with $^{13}C_6$ labelled Gal and Glc showed that both monosaccharides act as acceptor substrates in the transgalactosylation reactions. The data shows that the lactose isomers β-D-Gal*p*-(1 → 2)-D-Glc*p*, β-D-Gal*p*-(1 → 3)-D-Glc*p* and β-D-Gal*p*-(1 → 6)-D-Glc*p* are formed from acceptor reactions with free Glc and not by rearrangement of Glc in the active site.

1. Introduction

More than 200 human milk oligosaccharides (hMOS) have been identified in human mother milk, and they fulfill many functions in the health and development of the neonate (Barile & Rastall, 2013). In addition to providing nutrients for brain development, hMOS modulate intestinal immunity, block the binding of pathogens, and promote the growth of beneficial gut bacteria (Bode, 2012; Petherick, 2010). Nowadays many babies receive infant formula based on bovine milk, which has a more limited abundance and complexity of oligosaccharides (Bode, 2012). As an alternative route to provide beneficial oligosaccharides, analogues have been developed and added to infant formula to mimic the molecular sizes and prebiotic functions of hMOS (Boehm, Fanaro, Jelinek, Stahl, & Marini, 2003). These prebiotic analogues consists of short chain galactooligosaccharides (GOS), long chain fructooligosaccharides (FOS), polydextrose, and mixtures of these in different ratios (Boehm et al., 2003; Fanaro et al., 2005; Vandenplas, De Greef, & Veereman, 2015). Babies who received these analogues had significantly more Bifidobacteria in their gut microbiome than those in the placebo group (Oozeer et al., 2013). In addition, the species distribution of Bifidobacteria was more similar to that of the group receiving human mother milk (Oozeer et al., 2013).

β-Galactosidase enzymes are widely used in the dairy industry to convert lactose into GOS. They attack the anomeric center of the galactose residue in lactose, forming a galactosyl-enzyme complex while releasing the Glc molecule (Bultema, Kuipers, & Dijkhuizen, 2014; Gosling, Stevens, Barber, Kentish, & Gras, 2010; Torres, Gonçalves, Teixeira, & Rodrigues, 2010). The subsequent step depends on the acceptor substrate: if the acceptor is water, the galactosyl-enzyme complex undergoes hydrolysis and releases the Gal molecule as well; if lactose, monosaccharide or oligosaccharide serves as acceptor, GOS are formed as the transgalactosylation product. The previously formed disaccharide or oligosaccharide can either serve as a new acceptor substrate yielding GOS products with a higher degree of polymerization (DP), or bind to the enzyme to be used as a donor substrate (Supplementary Fig. S1). The linkage types and the DP of GOS produced depend on the specific enzyme and reaction conditions (Gosling et al., 2010; Torres et al., 2010).

Abbreviations: GOS, galactooligosaccharides; HPAEC-PAD, high-pH anion-exchange chromatography coupled with pulsed amperometric detection; NMR, nuclear magnetic resonance; MALDI-TOF-MS, matrix assisted laser desorption/ionization-time of flight mass spectrometry; Gal, galactose; Glc, glucose; Lac, lactose.

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Several commercial GOS products currently are available, such as Oligomate 55, Bimuno, and Vivinal® GOS (Otieno, 2010; Torres et al., 2010). Various microbial β-galactosidases are used for GOS synthesis, using relatively high lactose concentrations, yielding GOS mixtures with different structural compositions which are likely to result in different prebiotic effects (Otieno, 2010; van Leeuwen, Kuipers, Dijkhuizen, & Kamerling, 2016a).

β-Galactosidases from the bacterium *B. circulans*, the yeast *K. lactis* and the fungus *A. oryzae* are used in the dairy industry because of their high transgalactosylation activity and different ranges of products (Cataldi, Campa, & De Benedetto, 2000; Neri et al., 2009; Warmerdam, Zisopoulos, Boom, & Janssen, 2014; Zhou & Chen, 2001). Other formulations are produced using two enzymes, e.g. Oligomate 55 by the *A. oryzae* and *Streptococcus thermophilus* β-galactosidase enzymes (Torres et al., 2010). *B. circulans* β-galactosidase production yields 4 isoforms (BgaD-A, BgaD-B, BgaD-C, and BgaD-D), caused by truncation at the C-terminus of the BgaD protein (full length 1737 amino acids) (Song, Abe, et al., 2011). The shortest isoform (BgaD-D) contains 812 amino acids, and the crystal structure is a dimer (Ishikawa et al., 2015; Song, Imanaka, et al., 2011). At high lactose concentration, BgaD-D has a similar ability to produce GOS as the other isoforms (Warmerdam, Paudel, Jia, Boom, & Janssen, 2013). NMR analysis of Vivinal® GOS, the commercial GOS product made with the *B. circulans* β-galactosidase, has revealed more than 40 structures, covering 99% of the products (van Leeuwen, Kuipers, Dijkhuizen, & Kamerling, 2014, 2016b). The β-galactosidase from *K. lactis* consists of 1024 amino acids and the crystal structure is a tetramer (Pereira-Rodríguez et al., 2012). HPAEC-PAD analysis has revealed 6 structures in the *K. lactis* Lactozyme 3000 HG GOS product mixture, with a preference for (β1 → 6) linkages (Rodriguez-Colinas et al., 2011). The β-galactosidase from *A. oryzae* is a monomer with 985 residues (Maksimainen, Lampio, Mertanen, Turunen, & Rouvinen, 2013). The GOS molecules identified as products of this enzyme constitutes a mixture of 9 structures, among which β-D-Gal*p*-(1 → 6)-β-D-Gal*p*-(1 → 4)-D-Glc*p* accounts for nearly one-third of the total GOS (Urrutia, Fernandez-arrojo, Ballesteros, Wilson, & Plou, 2013).

Over the years, much effort has been devoted to optimize the reaction conditions of these 3 β-galactosidases to obtain a higher GOS yield. Several immobilization methods have been tested to enhance the stability of the enzymes (Benjamins, 2014; Gaur, Pant, Jain, & Khare, 2006; Kovács et al., 2014; Zhou & Chen, 2001). Different reaction temperatures and pH values have been used to improve the GOS yield (Palai, Mitra, & Bhattacharya, 2012; Vera, Guerrero, Conejeros, & Illanes, 2012). It has been suggested that the monosaccharides produced from lactose (Gal and Glc) inhibit the activity of the β-galactosidase enzymes from *A. oryzae*, *K. lactis*, and *B. circulans*, resulting in failure to reach the highest GOS yield (Gosling et al., 2010; Vera, Guerrero, & Illanes, 2011; Warmerdam, Wang, Boom, & Janssen, 2013). Several studies also have explored the transgalactosylation products of the 3 enzymes individually (Rodriguez-Colinas, Poveda, Jimenez-Barbero, Ballesteros, & Plou, 2012; Rodriguez-Colinas et al., 2011; Urrutia et al., 2013; Vera et al., 2012), and made a comparison between the 3 enzymes (Frenzel, Zerge, Clawin-Rädecker, & Lorenzen, 2015).

The reaction kinetic changes (Rodriguez-Colinas et al., 2012) of GOS fractions of these 3 β-galactosidase enzymes have not been studied yet. The aim of the present study is a comprehensive comparison of the complex GOS-synthesis process for three of the most prominent β-galactosidase enzymes currently used in industry. In this paper, the dynamic changes of the major GOS fractions produced by these 3 enzymes during the GOS synthesis process are presented. Also the influence of the monosaccharides (Gal and Glc) on GOS synthesis is studied in detail and compared among the 3 enzymes.

2. Materials and methods

2.1. Materials

β-Galactosidase from *K. lactis* (Lactozyme 2600L) and β-galactosidase from *A. oryzae*, Fucose, D-Glucose-$^{13}C_6$ (⩾99 atom% ^{13}C), and D-Galactose-$^{13}C_6$ (98 atom% ^{13}C) were purchased from Sigma-Aldrich (St. Louis, USA). Gal, lactose, Glc, sodium chloride, sodium hydroxide, sodium hydrogen phosphate, sodium dihydrogen phosphate, and sodium acetate were from Merck (Darmstadt, Germany).

2.2. Recombinant protein expression and purification

The C-terminally truncated *B. circulans* ATCC 31382 recombinant β-galactosidase (rBgaD-D) protein was constructed previously (Bultema et al., 2014) and used in this study. PCR amplification was performed in order to add a 6× His tag at the *N*-terminus of rBgaD-D. The template was plasmid pET-15b containing the rBgaD-D encoding gene. A forward primer (5′-CAGGGACCCGGTATG GGAAACAGTGTGAGC-3′) and reverse primer (5′-CGAGGA GAAGCCCGGTTATGGCGTTACCGTAAATAC-3′) were used for PCR amplification; the PCR products were purified on an agarose gel. Vector pET-15b-LIC was digested by FastDigest *Kpn*I (Thermo Scientific) and purified with a PCR purification kit (GE Healthcare). Subsequently, the PCR product was treated with T4 DNA polymerase (New England BioLabs) in the presence of 2.5 mM dATP, while the vector was digested with T4 DNA polymerase in the presence of 2.5 mM dTTP. Both reactions were incubated at room temperature for 60 min, followed by 20 min at 75 °C to inactivate the enzymes. The reaction mixture containing 2 μL of the target DNA and 1 μL vector was incubated at room temperature for 15 min to allow ligation. Then the mixture was transformed into *Escherichia coli* DH5α competent cells (Phabagen) for DNA amplification. The DNA sequence was verified by sequencing.

The plasmid containing the gene encoding the His-tagged rBgaD-D protein was transformed into *E. coli* BL21* DE3 competent cells (Invitrogen, Carlsbad, USA). Precultures of *E. coli* BL21* DE3 harboring the plasmid were grown overnight at 37 °C. Then 1% preculture was inoculated into fresh LB medium containing 100 μg/ml ampicillin. When the cell density reached 0.6 at 600 nm, the expression of His-tagged rBgaD-D was induced with 1 mM isopropyl-β-D-thiogalactopyranoside. Subsequently, the cells were cultured overnight at 30 °C and 220 rpm/min, and harvested by centrifugation. Cell pellets were washed with 20 mM Tris-HCl (pH 8.0) buffer and resuspended in B-PER lysis solution (ThermoScientific, Pierce). After incubation at room temperature for 30 min, the cell debris was removed by centrifugation. To purify the protein, the cell-free extract was mixed with HIS-Select® Nickel Affinity Gel (Sigma, USA), which was previously equilibrated with 20 mM Tris-HCl (pH8.0), 50 mM NaCl (buffer A), and incubated at 4 °C overnight. The unbound protein was washed away with 20 column volumes of buffer A, and then the rBgaD-D protein was eluted with buffer A containing 100 mM imidazole. The protein was centrifuged with a centrifugal filter with a cutoff of 30 kDa (Merck, Darmstadt, Germany) to remove the imidazole.

2.3. Enzyme incubations

2.3.1. Enzyme activity assays

The β-galactosidase activity towards lactose under relevant GOS production conditions was measured using an oxidase/peroxidase

method (GOPOD Format, Megazyme, Ireland). One unit (U) of (total) activity was defined as the enzyme amount required to release 1 μmol Glc per min. For rBgaD-D, 50% lactose (w/w) in 0.1 M sodium phosphate buffer (pH 6.0) was used as substrate (Park & Oh, 2010), incubated at 60 °C for 5 min. For Lactozyme 2600L, 30% lactose (w/w) in 0.1 M sodium phosphate buffer (pH 7.0) was used and the mixture was incubated at 40 °C for 5 min (Zhou & Chen, 2001). For the β-galactosidase from *A. oryzae*, 30% lactose (w/w) in 0.1 M sodium acetate buffer (pH 4.5) was used and incubation was carried out at 45 °C for 5 min (Vera et al., 2011). Different lactose concentrations were used reflecting the solubility of lactose at the respective enzyme optimum temperature. After 5 min, the reactions were stopped immediately by adding 1.5 M NaOH, followed by neutralization with 1.5 M HCl. The amount of released Glc was determined in the GOPOD assay by measuring the absorbance at 510 nm.

2.3.2. GOS synthesis

For the production of GOS from lactose, incubations of all 3 enzymes contained 37 U enzyme activity per gram lactose. The incubation conditions were: 50% lactose (w/w) in 0.1 M sodium phosphate buffer (pH 6.0), 60 °C for rBgaD-D; 30% lactose (w/w) in 0.1 M sodium acetate buffer (pH 4.5), 45 °C for β-galactosidase from *A. oryzae*; 30% lactose (w/w) in 0.1 M sodium phosphate buffer (pH 7.0), 40 °C for Lactozyme 2600L. At specified time intervals, 50 μL aliquots of reaction mixture were withdrawn and heated at 100 °C for 5 min to stop the reaction.

To analyze the synthesis of GOS products in time by the 3 β-galactosidases, 3.75 U enzyme activity per gram lactose was used for all 3 enzymes and incubated at their optimal conditions (see above). Aliquot samples were taken at 5 min, 15 min, 30 min, 1 h, 2 h, 4 h, and 8 h and immediately incubated at 100 °C for 5 min to stop the reaction.

The final GOS profiles were obtained by using 370 U enzyme activity per gram lactose for all 3 enzymes. The reactions were incubated at their optimal conditions for 72 h, 48 h, and 48 h for rBgaD-D, Lactozyme 2600L, and the β-galactosidase from *A. oryzae*, respectively.

2.3.3. Effects of Gal and Glc on GOS synthesis

To investigate the influence of the presence of the monosaccharides Gal and Glc on GOS synthesis, a mixture of 30% (w/w) lactose plus 20% (w/w) Gal or Glc was used for incubations with rBgaD-D. For Lactozyme 2600L and *A. oryzae* β-galactosidases, a mixture containing 20% (w/w) lactose plus 10% (w/w) Gal or Glc was used. The reactions were carried out using 37 U of the enzymes per gram lactose, incubated at their respective optimal conditions. The rBgaD-D enzyme also was incubated with 30% (w/w) lactose plus 20% (w/w) $^{13}C_6$ labelled Gal or 20% (w/w) $^{13}C_6$ labelled Glc as described above. All reactions were stopped after 2 h by incubation at 100 °C for 5 min. Structures of interest were isolated using preparative HPAEC-PAD separations.

2.4. HPAEC-PAD

For analytical HPAEC-PAD the reaction samples were diluted 3000 times with Milli-Q™ water, resulting in samples of ~0.10–0.17 mg/mL, containing 200 μM fucose as internal reference for the HPAEC-PAD analysis and quantification. The analysis of the samples was carried out with a Dionex ICS-3000 work station (ThermoScientific, Amsterdam, the Netherlands), coupled to a CarboPac PA-1 column (250 × 4 mm, Dionex) and an ICS-3000 ED pulsed amperometric detector (PAD). The separation conditions were the same as used previously (van Leeuwen et al., 2014). Briefly, the elution buffer consisted of a complex gradient of A) 100 mM sodium hydroxide, B) 600 mM sodium acetate in 100 mM sodium hydroxide, C) Milli-Q water, and D) 50 mM sodium acetate, details are provided in Supplementary Fig. S2. The quantification of GOS fractions is determined by the peak intensities of HPAEC-PAD profiles. GOS yield (%) = peak intensities of total GOS fractions/peak intensities of (galactose + glucose + lactose + total GOS fractions) * 100%. Percentage of specific GOS fraction (%) = peak intensities of specific GOS fraction/peak intensities of (galactose + glucose + lactose + total GOS fractions) * 100%. Preparative separations were performed on an ICS-5000 work station (ThermoScientific), coupled to a CarboPac PA-1 column (250 × 9 mm), using the same gradient as used for analytical separations at 4 mL/min. Samples were diluted to 4 mg/mL concentration and 250 μL was injected per separation. After separation samples were immediately neutralized using 4 M acetic acid, followed by desalting on Carbograph SPE (Grace, Breda, The Netherlands), eluting with 3 × 1 mL 40% acetonitrile in Milli-Q water.

2.5. MALDI-TOF-MS analysis

Positive-ion mass spectra were recorded on an Axima™ Performance mass spectrometer (Shimadze Kratos Inc., Manchester, UK) equipped with a nitrogen laser (337 nm, 3 ns pulse width). Spectra were recorded in reflectron mode at a resolution of at least 5000 FWMH and acquired with software controlled delayed-extraction optimized for m/z 800. Spectra were recorded with a range of 1–5000 m/z with ion-gate blanking set to 300 m/z. Samples were prepared by mixing on the target plate 1 μL sample solution (~1 mg/mL) with 1 μL matrix solution, consisting of 2,5-dihydroxybenzoic acid (10 mg/mL) in 40% acetonitrile.

2.6. NMR spectroscopy

The isolated oligosaccharide samples and the reaction mixtures were lyophilized and exchanged twice with 99.9% atom D_2O (Cambridge Isotope Laboratories Ltd, Andover, MA). Finally, samples were dissolved in 650 μL 99.9% atom D_2O, containing 25 ppm acetone (δ^1H 2.225, δ^{13}C 31.08) as internal standard. All NMR spectra, including 1D ^{1}H, as well as 2D ^{1}H-^{1}H and ^{13}C-^{1}H correlation spectra were recorded at a probe temperature of 298 K on a Varian Inova 600 spectrometer (NMR Department, University of Groningen, The Netherlands). 1D 600-MHz ^{1}H NMR spectra were recorded with 5000 Hz spectral width at 16 k complex data points, using a WET1D pulse to suppress the HOD signal. 2D ^{1}H-^{1}H spectra were recorded in 200 increments of 4000 complex data points with a spectral width of 5000 Hz. 2D ^{1}H-^{1}H TOCSY spectra were recorded with MLEV17 mixing sequences with 30, 60, and 150 ms spin-lock times. 2D ^{13}C-^{1}H HSQC spectra were recorded with a spectral width of 5000 Hz in t_2 and 10,000 Hz in t_1 direction. 2D ^{1}H-^{1}H ROESY spectra with a mixing time of 300 ms were recorded in 128 increments of 4000 complex data points with a spectral width of 5000 Hz. All spectra were processed using MestReNova 5.3 (Mestrelabs Research SL, Santiago de Compostela, Spain), using Whittaker Smoother baseline correction (Kamerling & Vliegenthart, 1992).

3. Results and discussion

3.1. Structures of GOS products

For each β-galactosidase enzyme a product profile was obtained after 4 h incubation at their respective optimal conditions (Fig. 1). GOS synthesized by rBgaD-D presents a mixture matching that of the commercial product of the native *B. circulans* enzyme, Vivinal® GOS (van Leeuwen et al., 2014, 2016b), here we only list the 21 major structures in Fig. 1. We also identified a total of 12, and 11

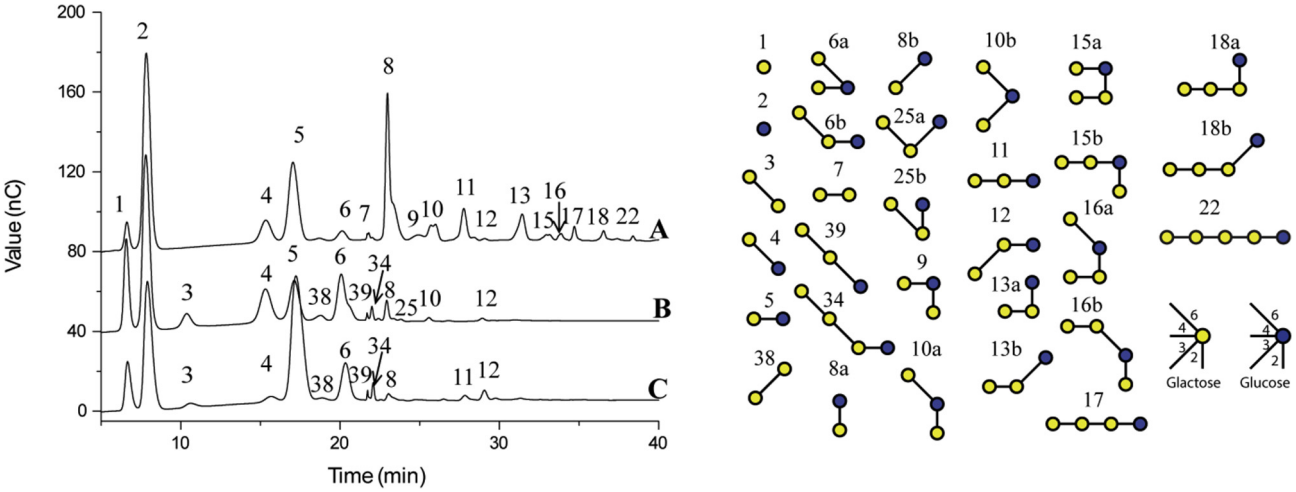

Fig. 1. HPAEC-PAD profiles (left) and GOS structures (right) produced from lactose by the 3 β-galactosidases, (A) rBgaD-D from *B. circulans*, (B) Lactozyme 2600L from *K. lactis*, (C) β-galactosidase from *A. oryzae*. The profiles were obtained after incubation for 4 h with the enzymes supplied at 37 U/g lactose. The determination of the GOS product structures was based on the retention times, NMR spectroscopy, and MALDI-TOF-MS (see Supplementary).

structures from the GOS profiles of Lactozyme 2600L and *A. oryzae* β-galactosidase, respectively. The GOS structures of peak **1**-**25a**, **34** and **38** were identified according to the GOS library described previously (Table S1) (van Leeuwen et al., 2014, 2016b, 2016a). Structure **39** [β-D-Gal*p*-(1 → 6)-β-D-Gal*p*-(1 → 6)-D-Glc*p*] was identified by matching the 1D ^{1}H NMR spectrum with that previously published (Beccati, 2009). Structure **25b** [β-D-Gal*p*-(1 → 6)-β-D-Gal*p*-(1 → 2)-D-Glc*p*] was identified by a combination of HPAEC-PAD profiling, MALDI-TOF-MS and NMR spectroscopy (Supplementary).

GOS synthesized by rBgaD-D presents a mixture showing (β1 → 4), (β1 → 2), (β1 → 3), (β1 → 6) linked Gal on the reducing Glc, with both linear and branched structures. All of these structures can be further elongated with (β1 → 4)-linked Gal residues. Structure **6b** (6′GalLac) with a (β1 → 6)-linked elongation of lactose, and structure **12** (3′GalLac) with a (β1 → 3)-linked elongation of lactose, were present only in trace amounts (Fig. 1).

In comparison, the GOS structures of the Lactozyme 2600L and *A. oryzae* β-galactosidase present much less complexity and variety. For *K. lactis* (Lactozyme 2600L) structures **3**, **4**, **6b**, **8b**, **12**, and **38** (Table S1) were previously identified, using Lactozyme 3000 HG (Rodriguez-Colinas et al., 2011). Structures **6a**, **8a**, **10a**, **10b**, **25a**, **25b**, and **39** (Table S1) had not been identified for the *K. lactis* β-galactosidase (Fig. 1), representing various peaks in the previous work that remained to be assigned (Rodriguez-Colinas et al., 2011). No structure **11** (4′GalLac) was observed here; possibly the Lactozyme 3000 HG preparation used by Rodriguez-Colinas et al. (2011) has slightly different activity and/or specificity.

For *A. oryzae* β-galactosidase structures **3**, **4**, **6b**, **8b**, **11**, **12**, **34** and **38** (Table S1) were observed both in this study as well as in previous work (Urrutia et al., 2013). Here, also **6a**, **8a**, and **39** were identified (Table S1, Fig. 1). Structure **7** [β-D-Gal*p*-(1 → 4)-D-Gal*p*] was not observed here but in the previous work (Urrutia et al., 2013).

The β-galactosidases from *K. lactis* and *A. oryzae* clearly showed a preference for (β1 → 6) elongation, reflected in structures **4**, **6a**, **6b**, **25a**, **25b**, **34** and **38** (Table S1, Fig. 1). There are some differences, however. GOS produced by Lactozyme 2600L showed two branched structures (peak **10a**, **10b**) stemming from (β1 → 6) substitution of the reducing Glc in structures **8a** and **8b**, respectively. GOS from *A. oryzae* β-galactosidase exhibited also (β1 → 4) elongating activity (peak **11**; 4′GalLac), which was not found in *K. lactis*. Overall, *K. lactis* β-galactosidase produced mainly (β1 → 6) elongations (peaks **3**, **4**, **6**, Fig. 1) while β-D-Gal*p*-(1 → 6)-β-D-Gal*p*-(1 → 4)-D-Glc*p* is the major structure produced by *A. oryzae* β-galactosidase, as previously reported by (Urrutia et al., 2013).

3.2. Formation routes of GOS structures

The synthesis of GOS products was followed in time for all 3 β-galactosidase enzymes, incubated at 3.75 U/g lactose (Fig. 2). From an analysis of the Vivinal product mixture it was previously observed that the commercially used *B. circulans* β-galactosidase is able to introduce all types of substitution on the reducing Glc residue (van Leeuwen et al., 2014, 2016b). When rBgaD-D was incubated with lactose and the reaction followed in time (Fig. 2A), first (β1 → 4) elongation of lactose occurred, resulting in structure **11** (4′GalLac). At 15 min (β1 → 4)-elongation of structure **11**to structure **17** occurred, followed by further (β1 → 4)-elongation to structure **22** at 60 min and to structure **24** at 120 min (Fig. 2A, Table S1). The first substitution structure of released Glc, by (β1 → 2)-elongation, i.e. [β-D-Gal*p*-(1 → 2)-D-Glc*p*] (structure **8a**) was observed at 15 min. Hydrolysis, as evidenced by free Gal in minor amounts (structure **1**), was also observed at 15 min. Further substitution of released Glc by (β1 → 3)-linked Gal, i.e. [β-D-Gal*p*-(1 → 3)-D-Glc*p*] (structure **8b**) was found at 30 min, and elongation of free Glc by (β1 → 6)-linked Gal [β-D-Gal*p*-(1 → 6)-D-Glc*p*] (allolactose; structure **4**) was observed at 60 min. Interestingly, the occurrence of 4,6-branched Glc in structure **6a** [β-D-Gal*p*-(1 → 4)-{β-D-Gal*p*-(1 → 4)-}D-Glc*p*] occurred already at 30 min, indicating it was not initially formed from allolactose (structure **4**). This branched structure could already be formed from (β1 → 6)-substitution of the Glc in lactose. At 60 min, all branched structures were found (**9**, **10a**, and **10b**, besides **6a** that was formed earlier), as well as the products of (β1 → 4) elongation of structures **8a** and **8b**, i.e. structures **13a** [β-D-Gal*p*-(1 → 4)-β-D-Gal*p*-(1 → 2)-D-Glc*p*] and **13b** [β-D-Gal*p*-(1 → 4)-β-D-Gal*p*-(1 → 3)-D-Glc*p*], respectively (Fig. 2A, Table S1). All these trisaccharides were further elongated in a (β1 → 4) manner in time up to the full DP5 spectrum at 240 min. The (β1 → 3) elongation of lactose (structure **12**) was only observed at 240 min, indicating that this reaction is less favorable for the enzyme.

With *K. lactis* β-galactosidase (Fig. 2B), (β1 → 6) elongation on the Gal unit of lactose (structure **6b**) was first observed at 5 min, followed by further (β1 → 6) elongation forming structure **34** at 60 min. The free Glc and Gal were released at 5 min. Then Gal

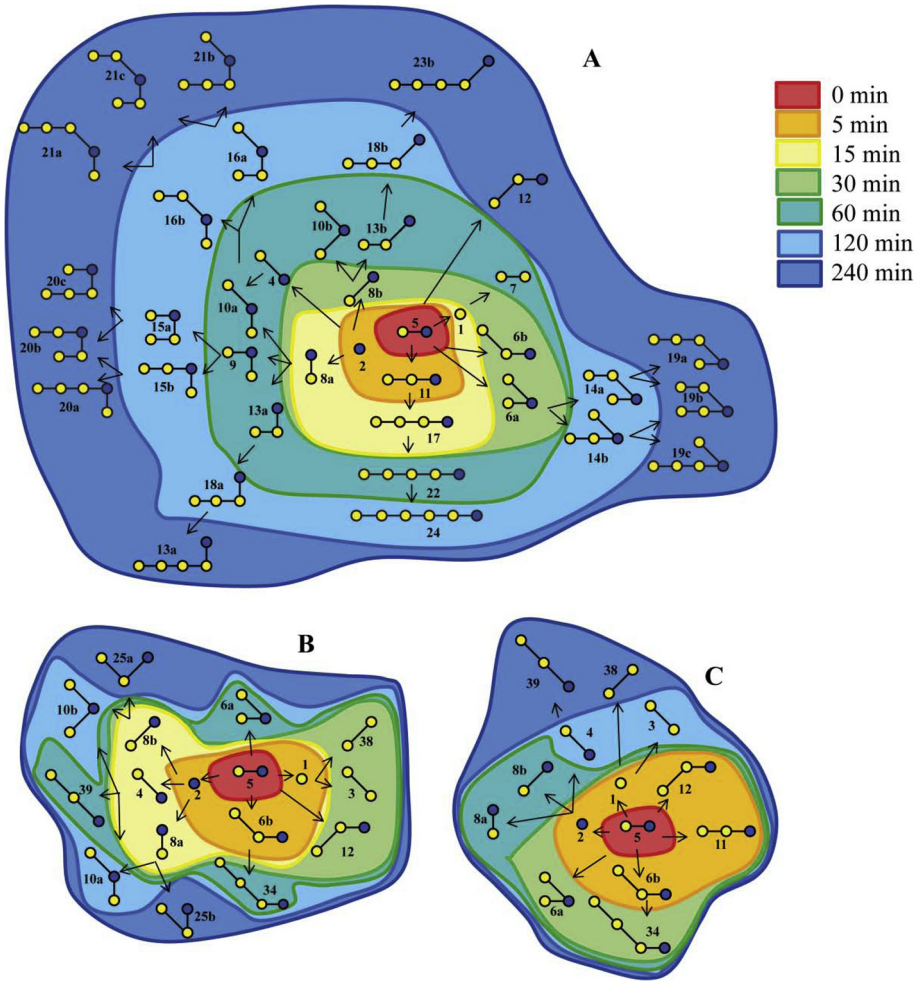

Fig. 2. GOS synthesis in time by the 3 β-galactosidases: (A) rBgaD-D of *B. circulans*, (B) Lactozyme 2600L from *K. lactis*, (C) β-galactosidase from *A. oryzae*. The arrows indicate the (possible) formation routes. The profiles were obtained using 3.75 U of the enzymes per g of lactose, incubated at the respective optimal conditions.

was further elongated by (β1 → 3) and (β1 → 6) linkages, forming structures **38** and **3** at 30 min, respectively. Meanwhile, the free Glc was used as acceptor, forming structures **4**, **8a**, **8b** at 15 min. These 3 structures were used for synthesis of structures **39**,**10a**, **10b**, **25a**, and **25b** (Fig. 2B, Table S1) from 60 min to 240 min. Structure **12** is a (β1 → 3) elongation of lactose on the Gal unit, it formed at 30 min. Structure **6a** is a (β1 → 6) branching of lactose on the Glc unit, it was found at 60 min.

In case of *A. oryzae* β-galactosidase (Fig. 2C), the (β1 → 6) elongation on lactose (structure **6b**) was first observed at 5 min, then further elongated with (β1 → 6), forming structure **34** at 30 min. Structures **11** and **12** were also formed at 5 min, by (β1 → 3) and (β1 → 4) elongation on lactose (Table S1). The free Gal and Glc were released at 5 min, then the Gal was elongated with (β1 → 6) and (β1 → 3) linkages forming structures **3** at 120 min, and structure **38** at 240 min, respectively (Fig. 2C, Table S1). Free Glc was used as acceptor substrate forming structures **8a** and **8b** at 60 min, and structure **4** at 120 min. Structure **4** was further elongated with (β1 → 6) linkage forming structure **39** at 240 min (Fig. 2C, Table S1). Structure **6a** was formed at 30 min by (β1 → 6) elongation on the Glc unit of lactose.

Analysis of the GOS synthesis profiles in time thus allowed deduction of the formation routes of the different GOS structures in time. This clearly revealed that rBgaD-D has a (β1 → 4) linkage preference while Lactozyme 2600L and *A. oryzae* β-galactosidases show a preference of (β1 → 6) linkage formation .

3.3. Changes of major GOS composition

The maximum GOS yields were calculated as follows (Table 1): rBgaD-D, 48.3 ± 1.2% GOS yield with 88.4 ± 0.4% lactose consumption at 8 h; Lactozyme 2600L, 34.9 ± 1.8% GOS yield with 91.8 ± 0.8% lactose consumption at 6 h; β-galactosidase from *A. oryzae*, 19.5 ± 2.2% GOS yield with 69.6 ± 1.1% lactose consumption at 8 h. The GOS composition and yield of β-galactosidase enzymes depend on the ratio between its transgalactosylation and hydrolysis. A high transgalactosylation/hydrolysis ratio is beneficial for GOS yield. When the GOS yield reached the highest points, the GOS/Gal factor was 10.9, 2.1, and 1.5 for rBgaD-D, Lactozyme 2600L, and *A. oryzae* β-galactosidase, respectively. This also explains why rBgaD-D has the highest GOS yield (Table 1).

The kinetic changes of the major GOS fractions produced by the 3 enzymes (Fig. 3) were followed by HPAEC-PAD integrations. Due to lack of suitable calibration standards, the assumption was used that all GOS structures have the same response on the PAD detector. Structure **11** is a (β1 → 4) elongation of lactose and the first GOS structure produced by rBgaD-D; it reached its highest yield at 45 min, then decreased quickly (Fig. 3A). Gal is only released in small amounts, indicating that the decline in **11** is the result of further transgalactosylation rather than of hydrolysis. Meanwhile structure **8** increased quickly in 5 h, and then stayed almost stable at longer incubation times. This may reflect the continued release of Glc from lactose, used as acceptor substrate for the

Table 1
Reaction time, lactose consumption, and GOS/galactose factor at the highest GOS yield of the three enzymes. The enzyme amounts and reaction conditions used are as shown in Fig. 2.

Enzyme source	GOS yield[1] (%)	GOS/Gal Factor[2]	Lactose consumption (%)	Reaction time[3] (h)
B. circulans	48.3 ± 1.2	10.9	88.4 ± 0.4	8
K. lactis	34.9 ± 1.8	2.1	91.8 ± 0.8	6
A. oryzae	19.5 ± 2.2	1.5	69.3 ± 1.1	8

[1] Determined from the peak intensities, data obtained by three parallel experiments. Only the peaks labelled in Fig. 2 (except lactose, Gal, and Glc) were used to determine the GOS yield.
[2] Representing the transgalactosylation/hydrolysis ratio, determined by the peak intensities of GOS and galactose.
[3] Reaction time at which the maximum GOS yield was obtained.

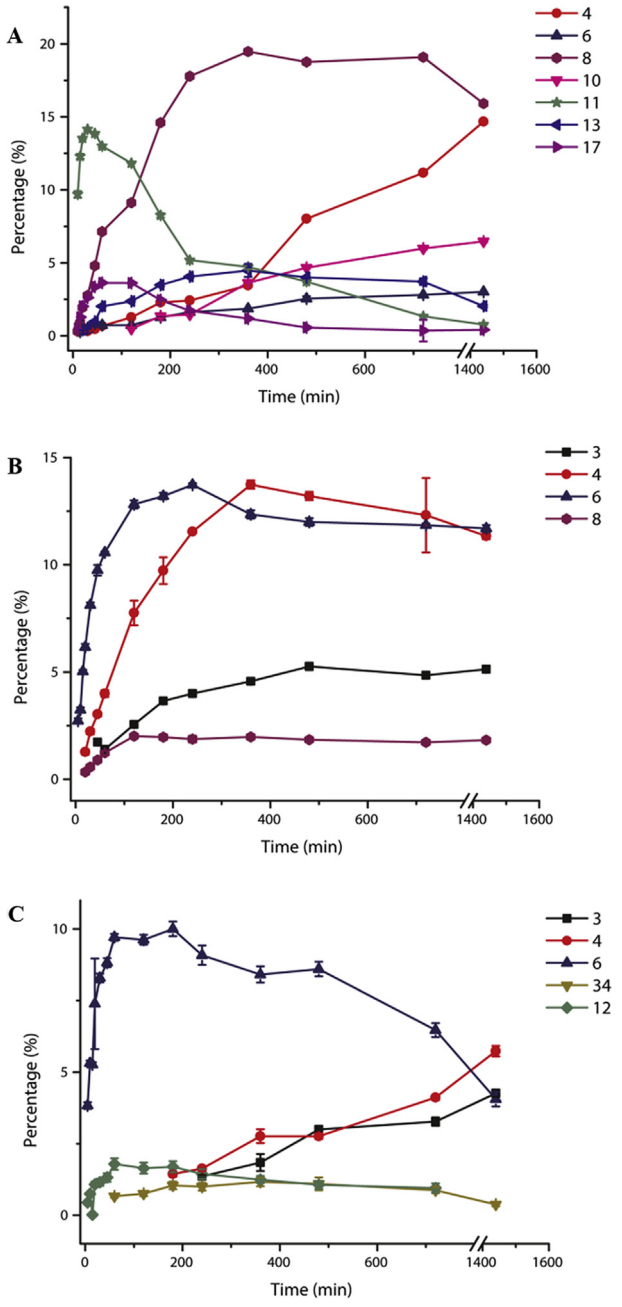

Fig. 3. Kinetic changes of major GOS fractions produced by the 3 β-galactosidases. (A) rBgaD-D from *B. circulans*, (B) Lactozyme 2600L from *K. lactis*, (C) β-galactosidase from *A. oryzae*. The enzyme amount and reaction conditions are the same as in Fig. 2. The numbers correspond to the peak numbers in Fig. 2. Data were obtained in three parallel experiments.

formation of **8a** and **8b**; both these structures also are used as acceptor substrate for (β1 → 4) elongation at similar rates. Structure **4**, allolactose, first increased gradually in 5 h, and then increased quickly. As a result, structures **8** and **4** became the major GOS structures upon longer incubation times with rBgaD-D (Fig. 3A). Fig. 3B showed that structures **4** and **6** are the major GOS fractions produced by Lactozyme 2600L, which reflects its strong preference for formation of (β1 → 6) linkages. Fig. 3C clearly showed that structure **6** is the major GOS fraction produced by *A. oryzae* β-galactosidase. It decreased gradually upon longer incubation times, while structures **3** and **4** increased gradually.

The kinetic changes in the major GOS fractions of these three enzymes showed that the GOS composition strongly depends on the enzyme source and is dynamically related to the reaction time.

3.4. The effects of Gal and Glc on GOS synthesis

To test whether Gal and Glc were just acceptor substrates, or whether they inhibited enzyme activity, reactions were performed with a high concentration of either monosaccharide from the start. The addition of Gal or Glc significantly changed the GOS profiles of all 3 β-galactosidase enzymes. For example, when Gal was added in the reaction with rBgaD-D, disaccharide β-D-Gal*p*-(1 → 4)-D-Gal*p* (structure **7**, Fig. 4A) increased significantly. This also resulted in appearance of an additional peak (structure **X**) in the product profile. This peak was isolated for NMR analysis and characterized as the (β1 → 4) elongation of structure **7** (trisaccharide β-D-Gal*p*-(1 → 4)-D-Gal*p*-(1 → 4)-D-Gal*p*) (Supplementary, Table S2). When Glc was used in the reaction, structure **8** had a much higher yield (Fig. 4A); also structure **4** increased. The changed GOS profiles clearly suggested that Gal and Glc were used as additional acceptor substrates. To investigate this in more detail, $^{13}C_6$ labelled Gal or Glc together with lactose were used in incubations with rBgaD-D. Structures **7**, **X** and **8** were isolated to check their masses using MALDI-TOF-MS (Fig. 5). The intensities of the peaks and the *m*/*z* showed that majority of structure **7** is formed from the $^{13}C_6$ labelled Gal, only a minority is formed from the normal Gal released during the reaction with lactose (Fig. 5A). Fig. 5B showed that the DP3 structure **X** contains mostly $^{13}C_6$ labelled Gal. Structures **8a** and **8b** contain both the $^{13}C_6$ labelled Glc and the normal Glc released during the reaction with lactose (Fig. 5C). These results confirm that Gal and Glc were used as acceptor substrates in the formation of GOS. The MALDI-TOF-MS analysis of the reaction mixture with $^{13}C_6$ Glc showed that the $^{13}C_6$ Glc was incorporated up to DP5 structures (Supplementary, Fig. S5).

These results indicate that structures **3** and **7** are only formed when enough Gal is released; this is also supported by the formation process followed in time (Fig. 2). Structures **4, 8a** and **8b** are only formed when a certain Glc threshold is reached, as was also evident when following the reaction in time (Fig. 2). Previously it was suggested that allolactose (structure **4**) particularly was

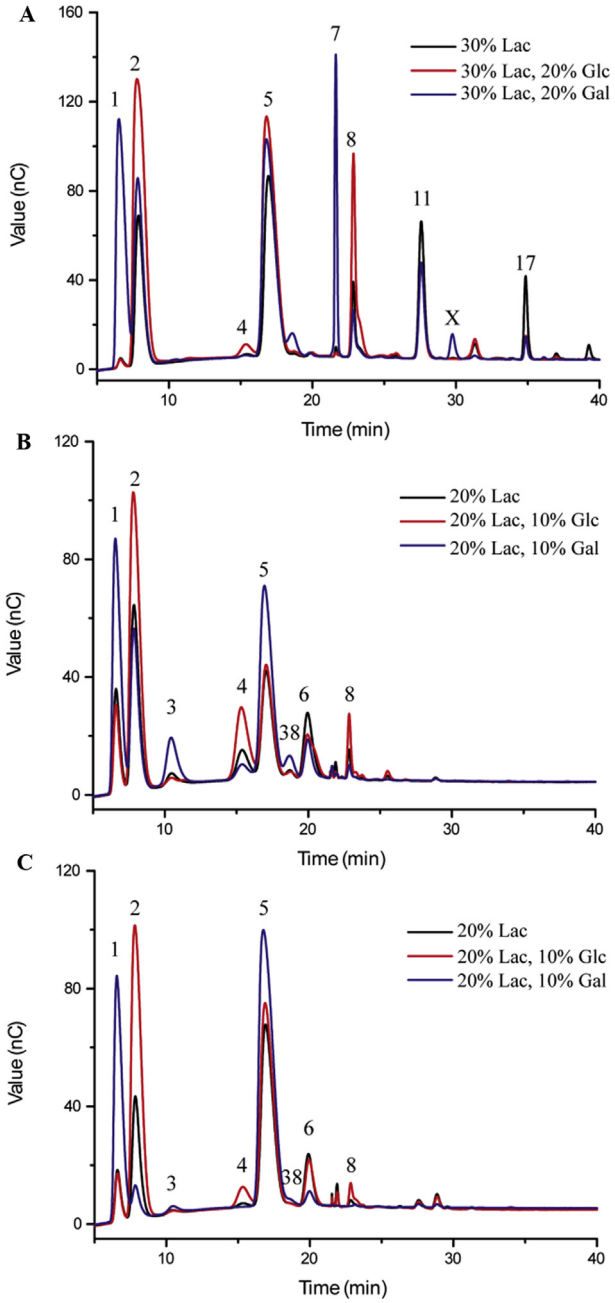

Fig. 4. The effects of Gal and Glc on the GOS profiles of the 3 β-galactosidases incubated with lactose: (A) rBgaD-D from *B. circulans*, (B) Lactozyme 2600L from *K. lactis*, (C) β-galactosidase from *A. oryzae*. Profiles were obtained using 37 U of the enzymes per g of lactose, incubated for 2 h at their respective optimal conditions. A mixture of 30% (w/w) lactose (plus 20% (w/w) Gal or Glc) was used for rBgaD-D. For the Lactozyme 2600L and *A. oryzae* β-galactosidases, a mixture containing 20% (w/w) lactose (plus 10% (w/w) Gal or Glc) was used.

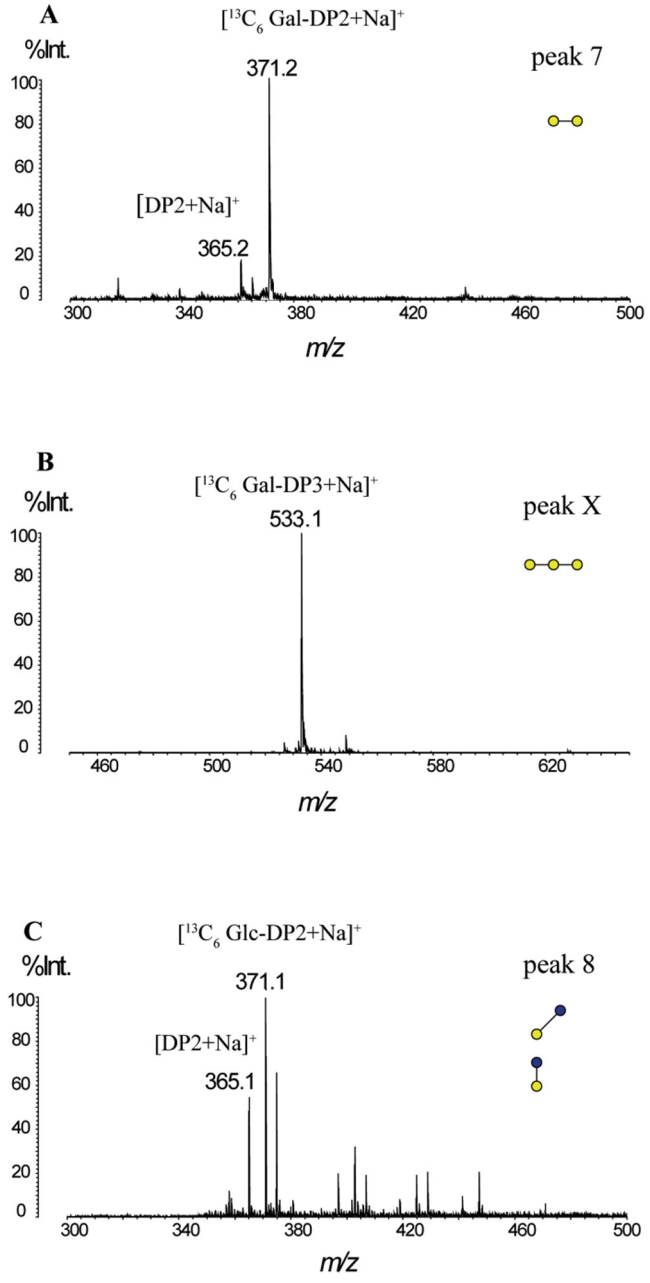

Fig. 5. MALDI-TOF-MS spectra of (A) structure **7**, (B) structure **X**, and (C) structure **8.** Compared to Fig. 5A, $^{13}C_6$ Gal or $^{13}C_6$ Glc were used in the incubations with lactose and rBgaD-D, then the peak fractions were isolated for MALDI-TOF-MS analysis.

formed from lactose by a rearrangement of the Glc in the active site of β-galactosidase from *E. coli* (Huber, Kurz, & Wallenfels, 1976). Our data, combined with the observations following the reaction in time, indicate that allolactose (structure **4**) as well as structures **8a** and **8b** were formed from Glc, acting as acceptor substrate in the transgalactosylation reaction catalyzed by the β-galactosidase from *B. circulans*.

When *K. lactis* β-galactosidase Lactozyme 2600L was incubated with 10% w/w Gal peaks **3** and **38** increased (Fig. 4B), showing that Gal can be used as an acceptor substrate as well. When incubated with Glc, peaks **4** and **8** increased, indicating that also Glc can be used as acceptor substrate by Lactozyme 2600L of *K. lactis.*

Addition of 10% w/w Gal to the incubation with β-galactosidase of *A. oryzae* resulted in a much lower GOS yield (Fig. 4C), indicating that Gal is an inhibitor for this enzyme; all peaks were reduced, also **3** and **38**, the (putative) products of the reaction with the Gal acceptor substrate. Adding Glc to the reaction resulted in increased levels of structures **4** and **8**, but to a lower extent than for the other two β-galactosidase enzymes.

3.5. Reaction end-point profiles

GOS generally are regarded as intermediate reaction products that ultimately will be hydrolyzed into Gal and Glc. In the above

we have studied the GOS product profiles at maximum yields. To study the final, end-point GOS profiles of each of the 3 enzymes, a high enzyme dose of 370 U/g lactose was incubated at the respective optimum conditions (Supplementary, Fig. S6). GOS initially produced by the Lactozyme 2600L and *A. oryzae* β-galactosidases were almost entirely hydrolyzed after prolonged incubation for 48 h (Fig. S5B and C). Peaks **3** and **4** represent the remaining disaccharides β-D-Gal*p*-(1 → 6)-D-Gal*p* and β-D-Gal*p*-(1 → 6)-D-Glc*p*. In contrast, there were still many GOS disaccharides and trisaccharides left in the rBgaD-D incubation, even after 72 h (Fig. S6A). An earlier study also reported that there were still large amounts of GOS and lactose left even after 400 h of incubation, and this was suggested to be caused by the inactivation of the Biolactase (commercial preparation of β-galactosidase from *B. circulans*) (Rodriguez-Colinas et al., 2012). A study on the stability of β-galactosidase from *B. circulans* showed that the enzyme retained 27% activity after incubation for 24 h at 60 °C in 30% (w/w) lactose solution (Warmerdam, Boom, & Janssen, 2013). The authors also indicated that a high initial lactose concentration had a large positive effect on the enzyme activity and stability. Our results showed that, when incubated with 50% (w/w) initial lactose at 60 °C, the enzyme retained 65% activity after 24 h, 37% activity after 48 h, and 28% activity after 72 h. In view of these results, it is unlikely that inactivation of the rBgaD-D enzyme can explain the remaining GOS and lactose in our study. Moreover, addition of a fresh dose of this enzyme after 48 h did not induce further changes in the final GOS profile (not shown).

4. Conclusions

This study has identified several parameters that influence the final GOS profiles of the β-galactosidases from *B. circulans*, *K. lactis*, and *A. oryzae*. Firstly, the β-galactosidase from *B. circulans* has a relatively high transgalactosylation/hydrolysis ratio (the GOS/Gal factor is 10.9, Table 1) in comparison with the other two enzymes, resulting in a high yield of GOS. The formation process of the rBgaD-D, showed a complex formation pattern (Fig. 2A), in which lactose analogues **8a**, **8b** and **4** were formed from acceptor reactions with released Glc, rather than rearrangement reactions with Glc retained in the active site. This was also evident from the observation that the lactose analogues were not formed until a certain level of free Glc was formed. This was further confirmed by reactions with added Glc, showing higher yields when Glc was present in high levels at the start of the reaction. Similar results were found for the *A. oryzae* and *K. lactis* enzymes, i.e. first free Glc was formed, and only later the lactose analogues were observed. The GOS formed by rBgaD-D s much more complex than the GOS from *A. oryzae* and *K. lactis* enzymes. Although the latter enzymes both had a preference for (β1 → 6)-elongation, there is a difference also. The *A. oryzae* enzyme can also synthesize (β1 → 3) and (β1 → 4)-elongations. The *K. lactis* enzyme showed a higher yield of complex GOS, but was unable to introduce (β1 → 4)-elongations.

Following the reactions to the end-point, it was observed that structures containing (β1 → 6) linkages, like β-D-Gal*p*-(1 → 6)-D-Glc*p* are difficult for rBgaD-D to hydrolyze, thus these structures are likely to accumulate during the reaction. For rBgaD-D the reaction ends in a dynamic equilibrium with relatively high amounts of structures with β-D-Gal*p*-(1 → 6)-elements. For *A. oryzae* and *K. lactis* enzymes the reaction ends with almost complete hydrolysis, showing only trace amounts of residual GOS after 48 h incubation with high enzyme activity.

Finally, the produced Gal and Glc did not inhibit the transgalactosylation reaction of rBgaD-D as shown in Fig. 5A; instead Gal and Glc can be used as acceptor substrates to synthesize GOS derivatives. Incubation with high initial Gal and Glc also showed that *K. lactis* is capable of effectively using both monosaccharides as an acceptor substrate and found no inhibitory effect. In the case of *A. oryzae* it was clear that Gal had an inhibitory effect on the enzyme, resulting in a lower GOS yield when incubated with a high starting concentration of Gal. In case of added Glc, similar GOS yields were achieved.

In summary, it is concluded that *A. oryzae* and *K. lactis* are enzymes with similar properties, but also showing minor differences in GOS production capacities. The *B. circulans* derived rBgaD-D enzyme produces a more complex product profile, and has a significantly higher transgalactosylation capacity, resulting in a more dynamic GOS profile, also at longer reaction times.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2017.01.030.

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