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Xylan derivatives and their application potential – Mini-review of own results

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ABSTRACT

The chemical modification of xylan is a promising path to new biopolymer ethers and esters with specific properties depending on the functional groups, the degree of substitution, and the substitution pattern. The reaction of 4-O-methylglucuronoxylan (GX) from birch with sodium monochloroacetate and 2,3-epoxypropyltrimethylammonium chloride in aqueous sodium hydroxide/slurry medium is described. The influence of the conditions of activation on product structure and properties are discussed in some detail. Methylation of GX was investigated under completely heterogeneous conditions or starting with dissolved polymer using methyl halides as reagents in the presence of NaOH. An activation of the biopolymer has been carried out before the reaction to enhance the accessibility of the reagents. Furthermore, novel xylan esters were efficiently synthesized by conversion of the hemicellulose with furan- and pyroglutamic acid as well as ibuprofen and N,N′-carbonyldiimidazole as activating agent under homogeneous conditions in dimethyl sulfoxide. This conditions are also appropriate to synthesize novel xylan ester containing xylan-4-[N,N,N-trimethylammonium]butyrate chloride moieties. Homogeneous syntheses of xylan sulfates could be carried out in a *N*,*N*-dimethylformamide (DMF)/LiCl as solvent applying sulfur trioxide complexes with DMF or pyridine. Advanced analytical techniques including NMR spectroscopy, HPLC, scanning electron microscopy, rheology, measurements of turbidity and surface tension allow description of structure–property-relationships; selected results will be briefly discussed. Xylan esters may form spherical nanoparticles of a size down to 60 nm and a narrow particle size distribution applying a simple dialysis process and may be used for drug delivery applications. For cationic xylan derivatives a wide range of applications as paper strength additives, flocculation aids, and antimicrobial agents are proposed.

1. Introduction

The hemicellulose xylan is one of the most abundant biopolymers present in hard wood and perennial plants such as grasses, cereals, and herbs. The most prevalently studied xylans are composed of a backbone of β-(1 → 4)-linked anhydroxylose units (AXU) (Cunha & Gandini, 2010; Ebringerová, 2005; Ebringerová & Heinze, 2000; Spiridon & Popa, 2008). Recently, xylan derivatives gain increasing importance as new biopolymeric based materials and functional polymers (Heinze, Koschella, & Ebringerova, 2004; Söderqvist Lindblad & Albertsson, 2004). Due to the functional properties of natural xylans various application fields are considered, e.g., xylans have gained increasing interest due to their potential as wound dressings (Lloyd, Kennedy, Methacanon, Paterson, & Knill, 1998) or pharmaceutical auxiliaries (Miraftab, Qiao, Kennedy, Anand, & Groocock, 2003). Xylans of higher molar mass from plantain interact with the complement system (Samuelsen et al., 1999), and glucuronoxylans from *Rudbeckia fulgida* are immunomodulating (Bukovský, Kardosová, Koscova, & Kostálová, 1998). Xylooligosaccharides are of interest due to their health benefits as prebiotics on the intestinal and their food flavour modifying characteristics (Crittenden & Playne, 1996; Gullón et al., 2010; Moure, Gullón, Dominguez, & Parajo, 2006) and acidic oligosaccharides containing uronic substituents possess their antimicrobial properties (Christakopoulos et al., 2003).

The application potential of biopolymers can be significantly enhanced by chemical derivatization. Xylan derivatives with non-ionic functions (e.g. pyroglutamate, furoate and ibuprofen esters of xylan as well as xylan propionates and hexanoates) could be synthesized by the reaction of the biopolymer with the activated carboxylic acid using N,N′-carbonyldiimidazol or with the acid anhydrides in the presence of methanesulfonic acid (Belmokaddem, Pinel, Huber, Petit-Conil, & Perez, 2011; Daus & Heinze, 2010; Heinze, Petzold, & Hornig, 2007; Heinze

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Table 1
Overview of xylans used (Daus et al., 2011; Petzold et al., 2006a, 2006b; Schwikal et al., 2006; Vega et al., 2012).

Source	Carbohydrate composition [%][a]							Mw [g/mol]
	Xyl	Ara	Rha	Glc	4MGA	GAUA	GLUA	
Birch	93.9	3.6	2.5	–	9.7	13 000		
Birch	73.0	10.1	4.2	–	2.9	4.1	0.7	10,700
Beech	87.2	2.6	–	7.0	1.7			1900

[a] Xyl xylose, Ara arabinose, Rha rhamnose, Glc Glucose, 4MGA 4-O-methylglucuronic acid, GAUA galacturonic acid, GLUA glucuronic acid.

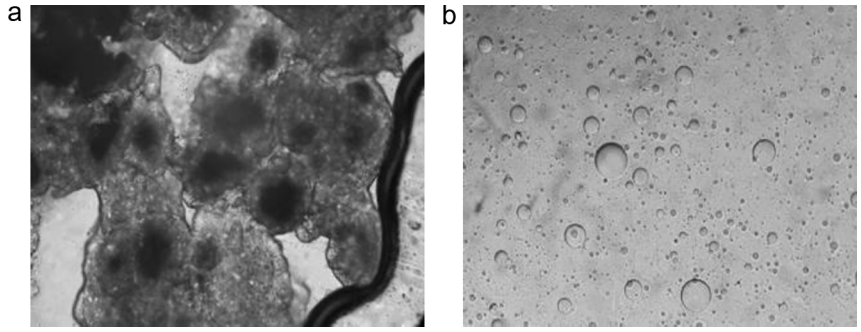


Fig. 1. Polarization microscopic illustration of xylan after activation (1 g xylan in 5 ml 25% NaOH and 7 ml 2-propanol): (a) xylan in 2-propanol followed by addition of aqueous NaOH, (b) xylan dissolved in 25% aqueous NaOH followed by addition of 2-propanol.

et al., 2004). For ionic functions, esterification of xylan, e.g., to xylan 4-[N,N,N-trimethylammonium]butyrates and maleates were developed using comparable conditions described above (Peng, Ren, & Sun, 2010; Vega, Petzold-Welcke, Fardim, & Heinze, 2012). The introduction of sulphuric acid half ester groups led to ionic esters (Daus et al., 2011; Simkovic, Gedeon, Uhliarikova, Mendichi, & Kirschnerova, 2011). Etherification using slurry processes were described in the literature for preparation of cationic xylans and anionic carboxymethyl xylan (Bigand et al., 2011; Heinze et al., 2004; Petzold, Schwikal, & Heinze, 2006a; Petzold, Schwikal, Günther, & Heinze, 2006b; Schwikal & Heinze, 2007; Schwikal, Heinze, Ebringerová, & Petzold, 2006). Recently, amphoteric xylan-type hemicelluloses having carboxymethyl- and quaternary ammonium groups prepared under microwave irradiation were described recently (Peng, Ren, Zhong, & Sun, 2012). The present article summarizes own results regarding etherification and esterification of 4-O-methylglucuronoxylan (GX) of different sources, especially from birch and beech, in detail (Table 1). The structure characterization and some property–structure relationships are described as well. Moreover, the application potential of the products is briefly discussed.

2. Ionic xylan derivatives

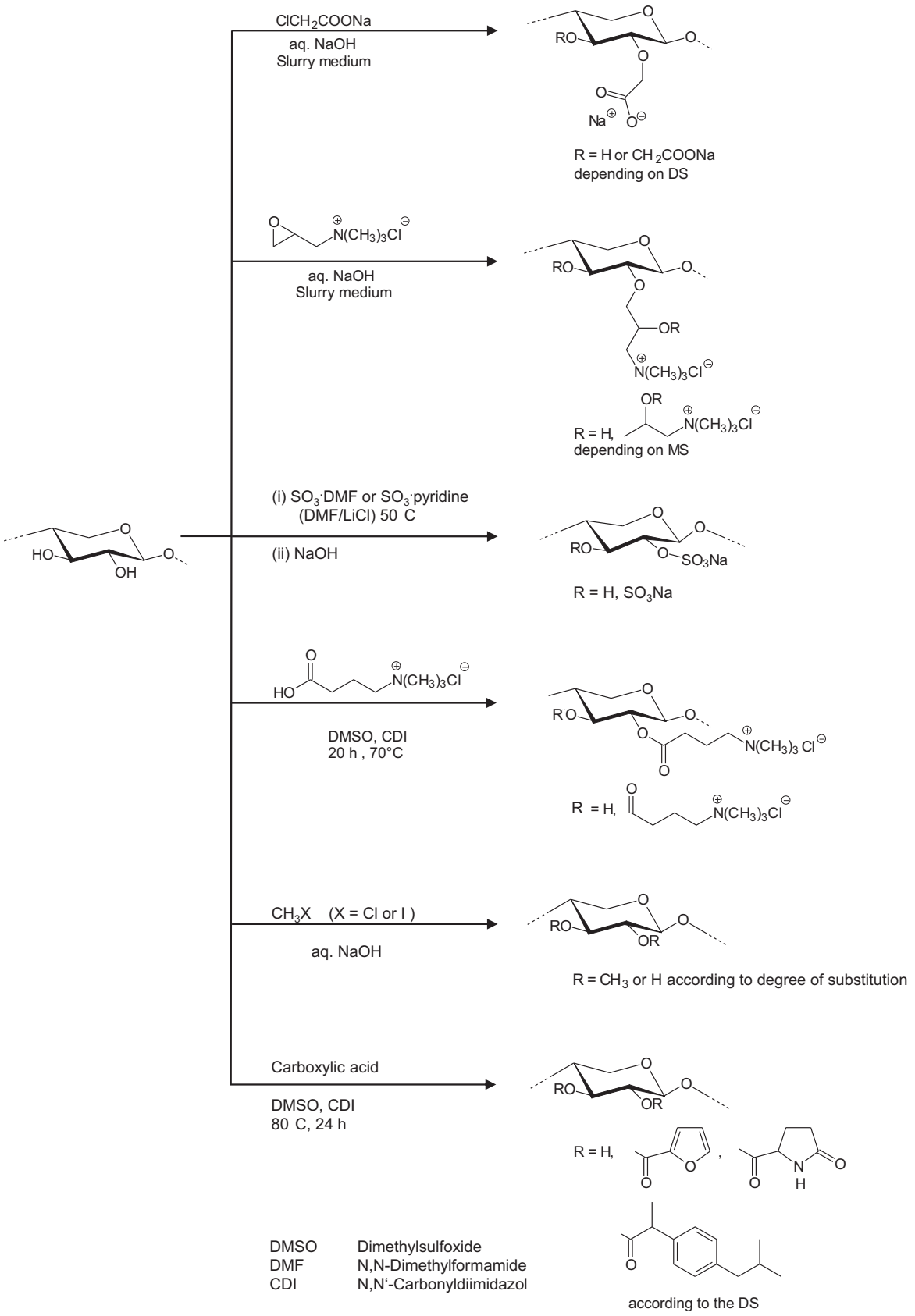
Anionic xylan derivatives based on GX, which was obtained from birch, can be obtained by the introduction of carboxylmethyl (CM) moieties. In addition, cationic xylan derivatives from birch wood GX are accessible by the functionalization with hydroxypropyltrimethylammonium (HPMA) groups (Scheme 1). In any case, an activation of the xylan is necessary to enhance the accessibility of the functional groups for the reagents. The activation could be carried out heterogeneously or starting from the dissolved polymer (Fig. 1, Petzold et al., 2006a; Schwikal et al., 2006). The heterogeneous activation starts with a stirred suspension of the xylan in the slurry medium, which is usually an alcohol or 1,2-dimethoxyethane (DME). The addition of aqueous NaOH leads to the activation of the xylan, however to an aggregated system (Fig. 1a). Otherwise, xylan could be dissolved in aqueous NaOH and precipitated by addition of 2-propanol yielding a uniform suspension and the activated xylan (Fig. 1b).

For the preparation of the anionic CM xylan (CMX), the biopolymer was mixed with 2-propanol followed by the addition of aqueous NaOH (heterogeneous activation). For the conversion (usually for 5 h at 55 °C), different molar ratios of sodium monochloroacetate (SMCA) to repeating unit were applied (Table 2). A different activation consists in the dissolution of xylan in 25% aqueous NaOH solution followed by addition of 2-propanol (homogeneous activation). Subsequently, SMCA was added and the reaction proceeds at 65 °C for 70 min (Table 2, Petzold et al., 2006a).

In both cases, the DS increases with increasing molar ratio of SMCA per anhydroxylose unit (AXU). By increasing the molar ratio from 1.0 mol SMCA per mol AXU to 10 mol SMCA/mol AXU, the DS increases from 0.39 to 1.09 in case of the complete heterogeneous carboxymethylation (heterogeneous activation). Surprisingly, no reaction occurred at a molar ratio of SMCA/AXU of 0.5 mol/mol. Starting with the dissolved polymer (procedure (ii) homogeneous activation, Table 2), the DS of the CMX obtained is in the range from 0.24 to 1.22 using molar ratio from 0.5 to 4.0 mol SMCA per

Table 2
Degree of substitution (DS) and substitution pattern of carboxymethyl xylan (CMX) obtained by the carboxymethylation of xylan (from birch, 5 g) with sodium monochloroacetate (SMCA) by (i) after heterogeneous activation (see text, carboxymethylation was carried out at 55 °C for 5 h) and (ii) after homogeneous activation (reaction was carried out at 65 °C for 70 min, adopted from Petzold et al., 2006a).

Molar ratio	Activation procedure	NaOH aq. [%]	DS (^{1}H NMR)		
AXU:SMCA:NaOH			At O-2	At O-3	Σ
1.0:0.5:0.5	(i)	15	–	–	–
1.0:1.0:1.0	(i)	15	0.29	0.10	0.39
1.0:1.5:1.5	(ii)	15	0.19	0.04	0.23
1.0:2.0:2.0	(i)	15	0.52	0.39	0.91
1.0:3.0:3.0	(i)	15	0.55	0.49	1.04
1.0:10.0:10.0	(i)	15	0.60	0.49	1.09
1.0:0.5:4.1	(ii)	25	0.20	0.04	0.24
1.0:1.0:4.1	(ii)	25	0.32	0.17	0.49
1.0:1.5:4.1	(ii)	25	0.39	0.13	0.52
1.0:2.0:4.1	(ii)	25	0.45	0.23	0.68
1.0:3.0:4.1	(ii)	25	0.57	0.49	1.06
1.0:4.0:4.1	(ii)	25	0.60	0.62	1.22



Scheme 1. Reaction paths for the preparation of xylan derivatives via etherification in aqueseous systems or esterification in DMF/LiCl DMSO.

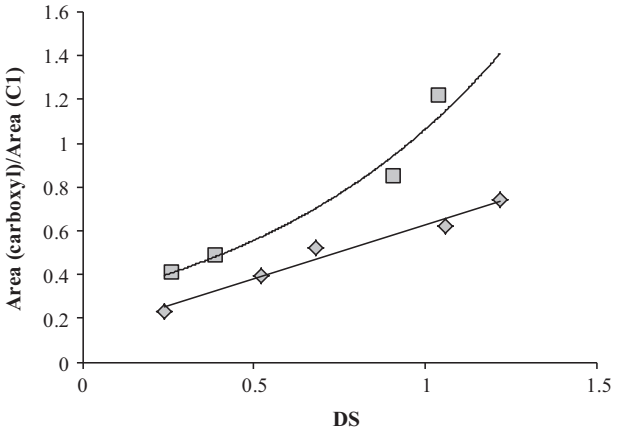


Fig. 2. Relation between the quotient of the integrals of the carboxyl peaks (173–178 ppm) and of the C1 signal (95–102 ppm) and the degree of substitution (DS) depending on the synthesis procedure (▫ complete heterogeneous carboxymethylation – heterogeneous activation, ◇ starting with dissolved xylan – homogenoueous activation).

(Reproduced with permission of John Wiley and Sons, Petzold, K., Schwikal, K., Günther, W., Heinze, T. (2006) Carboxymethyl xylan - Control of properties by synthesis, *Macromolecular Symposia*, *232*, 27–36). Copyright 2012.

mol AXU. Multi-step synthesis yielded products with DS values of up to 1.9 (Petzold et al., 2006a, 2006b).

Information about the pattern of substitution of the CMX was obtained by ^{13}C NMR spectroscopy in D_2O (Petzold et al., 2006b). Thus, the quotient of the integrals of the carboxyl peaks (173–178 ppm) and of the C1 signal (95–102 ppm) is plotted versus the DS_{NMR} determined by ^{1}H NMR spectroscopy after hydrolytic chain degradation (Fig. 2).

The longitudinal relaxation (T1) of the AXU carbons was complete, whereas the carboxyl carbons were not fully relaxed according data acquisition conditions applied (0.4 s to acquire the FID and 0.8 s relaxation delay). The curve progression is different depending on the synthesis path used. The curve of the samples synthesized under complete heterogeneous conditions (heterogeneous activation) proceeds in a nonlinear manner, i.e., the strong increase of the integral ratios with increasing DS is assumed to be caused by a noticeably decrease of the T1 of the carboxyl carbons indicating that the carboxyl groups are embedded in a more rigid environment in the case of the CMX from the heterogeneous activation than the CMX from the procedure starting with the dissolved polymer (homogeneous activation). These differences may result from a different functionalization pattern (Petzold et al., 2006b). To analyze the distribution of the substituents, the CMX samples were studied by HPLC after complete chain degradation. The sugar units obtained can be separated in un-, mono-, and di-O-carboxymethylated units employing ion exchange columns. Fig. 3a presents the mole fractions of the CMX synthesized after activation by dissolving the biopolymer and precipitation with 2-propanol (homogenous activation). The mole fractions fit the calculated values (Heinze, Erler, Nehls, & Klemm, 1994; Heinze, Heinze, & Klemm, 1999). In contrast, the mole fractions of the CMX prepared by a complete heterogeneous procedure (heterogenenous activation) differ from the calculated values (Fig. 3b). The polymers contain less mono-O-carboxymethylated units and more unsubstituted and di-O-carboxymethylated units, which may denote a non-uniform distribution of the CM functions within the polymer chains.

The above-stated different synthesis pathways for the preparation of CMX can be adapted to the synthesis of other ethers including hydroxypropyltrimethylammonium xylans (HPMAX). In contrast to carboxymethylation, a comparatively low

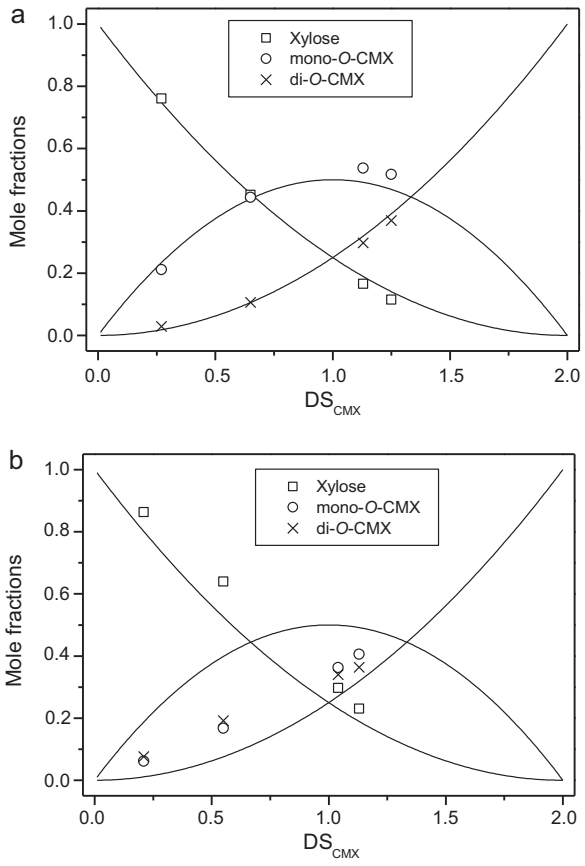


Fig. 3. Mole fractions of the repeating units (xylose, mono-O-carboxymethyl xylose, di-O-carboxymethyl xylose) of carboxymethyl xylan (CMX) samples synthesized (a) after activation by dissolving the biopolymer and precipitation with 2-propanol (homogeneous activation) and (b) heterogeneous activation as a function of the degree of substitution (DS) (detected by HPLC after acidic chain degradation with HClO4). The curves were calculated by $c_u = (1\text{-}DS/2)2$, $c_{mono} = DS(1\text{-}DS/2)$, $c_{di} = (DS/2)2$ with $k2 = k3$.

(Reproduced with permission of John Wiley and Sons, Petzold, K., Schwikal, K., Günther, W., Heinze, T. (2006) Carboxymethyl xylan – Control of properties by synthesis, *Macromolecular Symposia*, *232*, 27–36). Copyright 2012.

concentration of NaOH could be used. The syntheses were carried out with 2,3-epoxypropyltrimethylammonium chloride (EPTA) in DME as slurry medium. The xylan was dissolved in 4% aqueous NaOH and DME was added subsequently (homogeneous activation). Depending on the molar ratio of the EPTA to the AXU (0.5–10.0) molar degrees of substitution (MS) between 0.2 and 1.7 are accessible (Fig. 4, Schwikal et al., 2006).

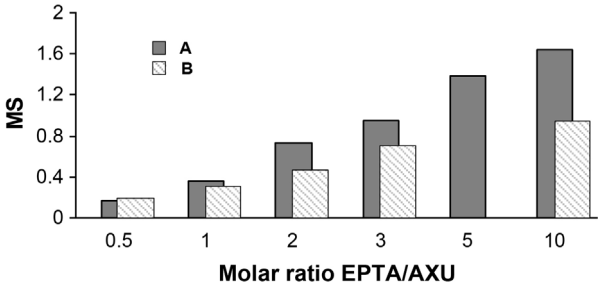


Fig. 4. Molar degrees of substitution (MS) of hydroxypropyltrimethylammonium xylans (HPMAX) depending on the molar ratio of epoxypropyltrimethylammonium chloride (EPTA) to anhydroxylose (AXU) in the synthesis. (A) Starting with dissolved xylan–homogenous activation and (B) heterogeneous activation (Schwikal, 2007).

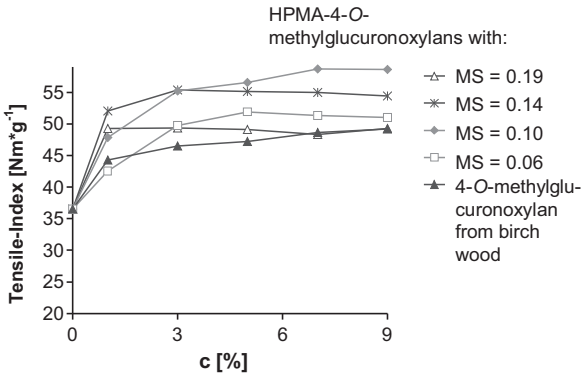


Fig. 5. Tensile strength of birch sulfate pulp as a function of concentration per pulp for added 4-methylglucurono xylan (GX) or 2-hydroxypropyltrimethylammonium xylan chloride (HPMAX) with different MS. Values for the untreated pulps correspond to the data points at $c = 0$. The detailed experimental conditions are in the referred publication. The pulp was refined for 2.5 min before the HPMAXs was added, but 10 min refining time were also used. The percentage in the increase compared to the papers without additive are in the same range for both 10 and 2.5 min refining time for HPMAX with a MS of 0.1.

(Reproduced with kind permission of Springer Science & Business Media, *Cellulose*, *18*, 2011, 727–737, Properties of spruce sulfite pulp and birch kraft pulp after sorption of cationic birch xylan. Schwikal, K., Heinze,T., Saake, B., Puls, J., Kaya A., & Esker A. R., Fig. 2). Copyright 2012.

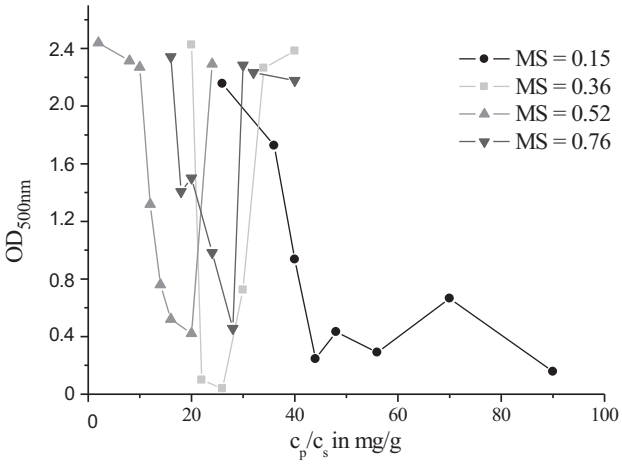


Fig. 6. Optical density (OD) of a suspension of china clay (pH = 8.8; solids content 1 g/l) in dependence on the molecular degree of substitution (MS) and the amount and of 2-hydroxypropyltrimethylammonium xylan (HPMAX) per china clay (*cp*/*cs* (mass ratio of polymer to substrate, adopted from (Schwikal, 2007).

In addition, HPMAX derivatives with MS above 2 are obtained by multi-step syntheses; a derivatization of the newly formed hydroxyl group during the ring opening reaction of the epoxide occurs. The opposite pathway, suspending xylan in DME and subsequently adding 4% aqueous NaOH solution (heterogeneous activation), yields HPMA xylans with a MS depending on the molar ratio of the EPTA to the AXU (Fig. 4). A comparison between the HPMAX obtained after both activation methods shows that even at higher molar excess (starting with 2 mol EPTA per mol AXU) a better conversion of the xylan activated by dissolution prior the reaction occurs (homogeneous activation, Schwikal et al., 2006; Schwikal, 2007).

Despite nearly the same MS, a selective enzymatic degradation with an endoxylanase (Ecopulp TX-200C Lot 10317413, Röhm Enzyme Finland Oy) and subsequent fractionation via SEC shows differences in the resulting oligomeric chain lengths (Schwikal, 2007). These findings indicate a different substituent distribution along the polymer chain due to different activation procedures prior the preparation of the xylan derivatives.

The distribution of the substituents controlled by the activation procedure has a strong influence on the properties of both derivatives (CMX and HPMAX). A typical example of differences is the surface tension of the samples (1% solution, Table 3, Schwikal, 2007). Both, the CMX and the HPMAX synthesized under completely heterogeneous conditions (heterogeneous activation) show a higher decrease of the surface tension of water than those prepared starting with the dissolved xylan (homogeneous activation).

HPMAX was studied regarding potential applications as paper additive and flocculation aid (Figs. 5 and 6). As seen in Fig. 5, the addition of GX enhances the tensile modulus compared to the untreated pulp (data point at zero concentration) as reported by Schönberg, Oksanen, Suurnäkki, Kettunen, & Buchert, 2001. But more important, the addition of 9% (w/w) HPMAX with a MS of 0.1 to the pulp led to the maximum tensile index that is increased by 60% compared to untreated pulp and 19% compared to GX treated pulp (birch sulfate pulp). HPMAX with lower and higher MS yield a smaller improvement in the tensile index that depended on the pulp source. The results of the increase of the paper strength by addition of HPMAX from birch xylan is in the same range like found for cationic starch, which is widely used in paper making (Schwikal, Heinze, Saake, Puls, Kaya, & Esker, 2011). It might be assumed that the dependence of the tensile index on the MS of the added HPMAX is their self-structuring behaviour in solution, electrostatic interactions and related to this their adsorption tendency (Köhnke, Brelid, & Westman, 2009; Linder, Bergman, Bodin, & Gatenholm, 2003). Moreover, it is interesting to note that HPMAX adsorption onto SAM-COOH surfaces studied with surface plasmon resonance spectroscopy strongly correlated with tensile strength tests of the pulps. For the SAM-COOH surface, HPMAGX adsorption exhibited a clear maximum with respect to MS at a value of 0.10. The weaker adsorption for $0.10 < MS > 0.10$ is consistent with a net negative charge on HPMAGX and intra-chain electrostatic repulsion between cationic groups on HPMAGX that led to flatter adsorbed conformations. The strong adsorption on the SAM-COOH surface of the HPMAX leads to the conclusion that electrostatic interactions play the dominant role for enhancing the increase of the tensile index when HPMAX are added to pulp (Schwikal et al., 2011).

Preliminary results about the flocculation behaviour of HPMAX onto china clay suspensions gave promising results (Fig. 6). The best flocculation behaviour was observed for the HPMAX with an MS of 0.36; a fast flocculation with big flocks and a clear supernatant liquid were generated. Compared with other cationic biopolymers, e.g., cationic starch (Bratskaya et al., 2005), the amount of the HPMAX needed was higher.

Although the exact mechanism is not fully understood, it is well known that polymers with a high positive charge like cationic starches with DS values of 0.4–3.0 and chitosan would be expected to have an antimicrobial activity (Haack et al., 2002; Rejane, de Britto, & Assis, 2009). For different xylan derivatives with a high content of cationic moieties, the antimicrobial activity was tested against various bacteria and the fungi *Candida albicans*. The HPMAX studied with a MS of 0.36 shows an antimicrobial activity against *Mycobacterium vaccae* 10,670 and the sample with a MS of 0.6 against *Staphylococcus aureus* SG511 and 134–64. The growing of the *Escherichia coli* SG458, *Enterococcus faecalis* 1528 and *C. albicans* C.A. was not significantly inhibited. An antimicriobial activity was shown the lower minimal inhibition dose the higher the MS of the HPMAX. Comparing to ciprofloxacin the effect of the HPMAX with a MS of 1.38 against *S. aureus* 134–64 is nearly the same and against *S. aureus* SG511 and *M. vaccae* 10,670 the minimal inhibition dose is slightly higher (Schwikal, 2007).

The sulphation of xylans of different plant origin was studied in *N*,*N*-dimethylformamide (DMF)/LiCl as solvent using SO_3-complexes with DMF and pyridine as sulphating agents (Scheme 1).

Table 3
Surface tension of 1% aqueous solution of carboxymethyl xylan (CMX) and 2-hydroxypropyltrimethylammonium xylan chloride (HPMAX) depending on the activation procedure used for synthesis.

Carboxymethyl xylan obtained after				2-Hydroxypropyltrimethylammonium xylan chloride obtained after			
Homogeneous activation		Heterogeneous activation		Homogeneous activation		Heterogeneous activation	
DS	Surface tension [mN/m][a]	DS	Surface tension [mN/m][a]	MS	Surface tension [mN/m][a]	MS	Surface tension [mN/m][a]
0.25	61.2	0.23	49.4	0.17	59.5	0.20	43.2
0.52	57.4	0.39	45.5	1.00	56.6	0.31	41.6
1.22	60.0	1.04	52.6	1.38	57.9	0.95	53.2

Adopted from Schwikal (2007).
[a] Surface tension of pure water: 72.7 mN/m.

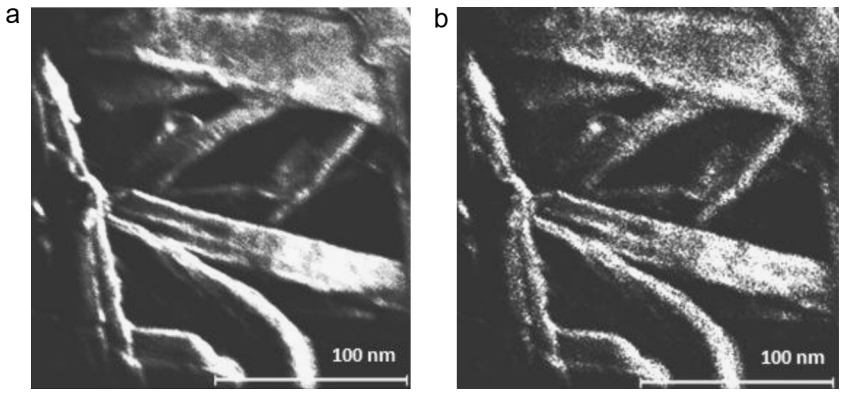


Fig. 7. ToF-SIMS images in positive mode of total secondary ions for a transverse section of bleached Kraft pulp treated with xylan-4-[N,N,N-trimethylammonium]butyrate chloride (XTMAB) (a) and XTMAB characteristic ions with signal at $m/z = 58$ and $m/z = 146$ for the same sample (b).
Reproduced from Vega, B., Petzold-Welcke, K., Fardim, P., & Heinze, T., *Carbohydrate Polymers*, *89*,768–776, 2012, Studies on the fibre surfaces modified with xylan polyelectrolytes, with kind permission of Elsevier. Copyright 2012, with permission from Elsevier.

The DS of the products could be controlled by varying the molar ratio of the sulphating reagent to AXU. However, the DS value accessible strongly depends on the source and hence of the structure of the xylan. A maximum DS of 1.90 was obtained with purified xylan from beech wood by applying 3 mol SO_3/pyridine per mol AXU. Structural differences of xylan sulphates can be identified by NMR spectroscopy (Daus et al., 2011).

Xylan sulphates inhibit the cytopathic effect (CPE) of *herpes simplex viruses* on green monkey kidney cells. The antiviral activity proved to be dependent on the structure and the $DS_{Sulphate}$. Xylan sulphates with higher molar mass containing side groups (oat spelt xylan contains arabinose, birch wood xylan 4-O-methyl-glucuronic acid) proved an antiviral activity with DS values > 1.2. Low molecular weight xylans, however, have to exceed DS values of 1.7 to possess similar activities.

A DS dependent interaction of xylan sulphates with antithrombin III and a resulting blood coagulation inhibition was identified. Xylan sulphuric acid half esters of low molecular weight xylan from beech wood with a $DS_{Sulphate}$ of 1.79 increased the activated partial thromboplastin time (APPT) of blood serum from 41.8 s to 74.2 s (Daus, 2010).

Recently, the synthesis of the cationic xylan-4-[N,N,N-trimethylammonium]butyrate chloride (XTMAB) was carried out by esterification of xylan with 3-carboxypropyltrimethylammonium chloride in the presence of N,N′-carbonyldiimidazol under homogeneous condition in DMSO (Scheme 1). The cationic xylan ester was used for studying the sorption properties in cellulose fibres. XTMAB adsorbed to the fibres and a saturation level was reached when 70 μequiv. of the xylan ester per gram of pulp was used. The presence of XTMAB onto the fibres surface could be proved by the ToF-SIMS analysis of the modified fibres surface (after treatment with XTMAB); very intense signals at $m/z = 58$ and $m/z = 146$ were found. In addition, ToF-SIMS imaging was used to study the distribution of the XTMAB onto the fibre surfaces by monitoring $[H_2C\ N^+(CH_3)_2]$ and $[HOOC(CH_2)_3N^+(CH_3)_3]$ ions (Fig. 7). The XTMAB polymers were quite homogeneous distributed on the fibres and the polymer covered evenly the surface (Vega et al., 2012).

3. Non-ionic xylan derivatives

The methylation of xylan (methylglucuronoxylan from birch) was studied with methyl chloride or methyl iodide in the

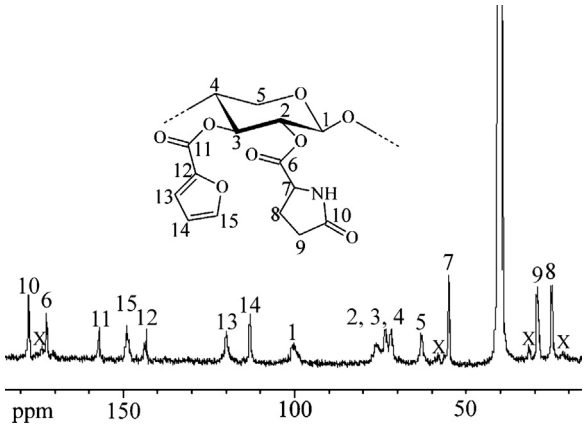


Fig. 8. ^{13}C NMR spectrum of xylan furoate pyroglutamate mixed ester (substitution degree, $DS_{Furoate}$ 0.67, $DS_{Pyroglutamate}$ 0.78) in DMSO-d6 (X indicates the signals resulting from pyroglutamic moieties located at the 4-O-methylglucopyranosyl uronic acid side groups).
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Table 4
Degree of substitution (DS) of unconventional xylan esters (xylan furoate-pyroglutamate mixed esters and ibuprofen esters) as function of the molar ratio of reagent (conversion at 80 °C for 20 or 24 h) and particle size of the nanospheres obtained by dialysis (Daus & Heinze, 2010; Heinze et al., 2007).

Xylan	Molar ratio				Xylan ester[a]				
	AXU	FCA	PGA	Ibuprofen	DS_F	DS_P	DS_I	Σ DS	Particle size [nm]
Birch	1	2	2	–	0.67	0.78	–	1.45	85
Birch	1	3	3	–	0.74	0.74	–	1.48	73
Beech	1	–	–	1	–	–	0.79	–	328
Beech	1	–	–	2	–	–	1.24	–	473

[a] DS_F DS of furoate moieties, DS_P DS of pyroglutamate groups, DS_I DS of ibuprofen esters.

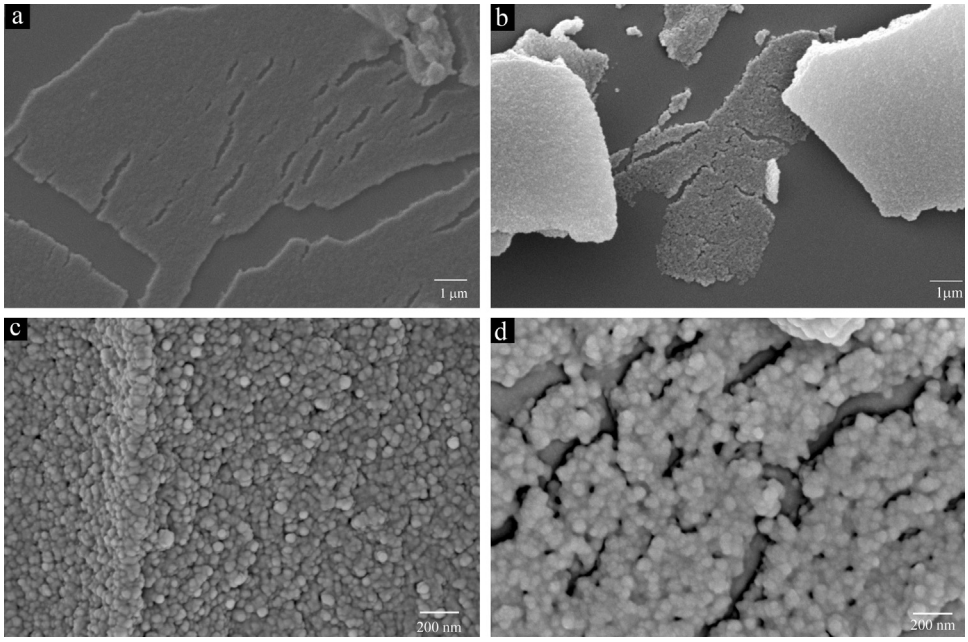

Fig. 9. SEM images of nanoparticles of xylan furoate pyroglutamate mixed ester (a) and (c) substitution degree ($DS_{Furoate}$) 0.67 and $DS_{Pyroglutamate}$ 0.78) and (b) and (d) $DS_{Furoate}$ 0.74, $DS_{Pyroglutamate}$ 0.74 in different scale.
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presence of aqueous NaOH (Scheme 1, Petzold, Günther, Kötteritzsch, & Heinze, 2008).

The methylation with a high excess of methyl chloride (19 mol/mol AXU) under pressure (12 bar) in the presence of 40% aqueous NaOH leads to a partially methylated xylan ether (DS 0.94). The reaction of xylan with methyl iodide in the presence of 25% aqueous NaOH for 5 h at room temperature yields methyl xylans with DS of about 0.5 independent of the molar ratio in the range of 0.5–3.0 mol reagent per mol AXU. At a molar ratio of 1.0–4.0 (AXU to methyl iodide), a product with a higher DS of 0.76 resulted. In a mixture of 25% aqueous NaOH and acetone as slurry medium, the reaction with methyl iodide results in methyl xylans with DS values of 0.41–0.51 independent of the molar ratio (0.5–4.0 mol methyl iodide per mol AXU) too. That means that no change of DS occurred; the differences are in the margin of error. By means of two-dimensional NMR techniques, mono-2-O-methylated, di-2,3-O-methylated and unsubstituted units can be identified in the polymer chain of methyl xylans as well as the methylglucuronic acid residue. No clear identification of the 3-mono-O-methylated anhydroxylose unit was possible by using these NMR techniques.

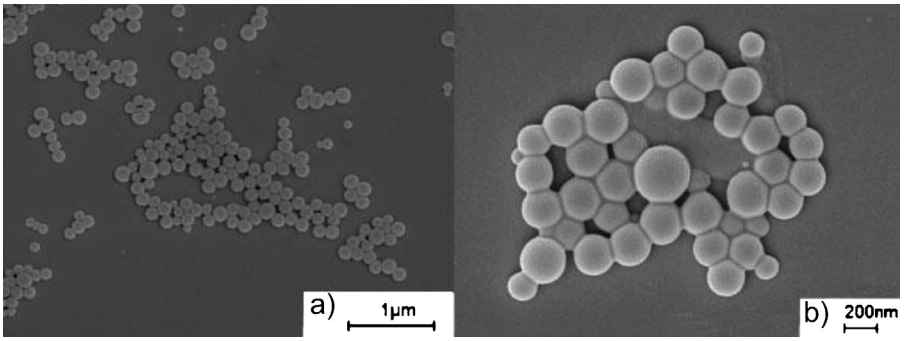

Fig. 10. SEM images of nanoparticles of xylan ibuprofen esters prepared by dialysis: (a) DS_{Ibu} 0.79, (b) DS_{Ibu} 1.24.
Reproduced with permission of John Wiley and Sons, Daus, S., & Heinze, T. (2010). Xylan-Based Nanoparticles: Prodrugs for Ibuprofen Release, *Macromolecular Bioscience*, *10*, 211–220. Copyright 2012.

Methyl xylans are soluble in water under heating and do not precipitate by cooling. A 5% aqueous solution of methyl xylan (DS of 0.94) possesses a low shear viscosity (1–5 mPa s) even at a low shear rate (measured with a Rheostress 150 rheometer, HAAKE, Karlsruhe, Germany). Preliminary studies show that this methyl xylan decreases the surface tension to 40.4 mN/m compared to pure water (72.7 mN/m). It became obvious that the sample possesses a certain amphiphilicity (Petzold et al., 2008).

For esterification, xylan isolated from birch or beech was dissolved in dimethyl sulfoxide (DMSO) and allowed to react with furan-2-carboxylic acid and pyroglutamic acid to form a mixed ester, or with ibuprofen in the presence of N,N′-carbonyldiimidazole (CDI) as an activating agent (Scheme 1, Daus & Heinze, 2010; Heinze et al., 2007).

CDI is very efficient in the synthesis of tailored polysaccharide esters. Non-toxic and easily removable by-products (CO_2, imidazole) are formed. Due to neutral reaction conditions almost no polymer degradation occurs (Heinze, Liebert, & Koschella, 2006). Depending on the molar ratio of the acids used, xylan esters with a varying degree of substitution (DS) were obtained (Table 4).

The reaction conditions used for the mixed esters give products with DS values of the pyroglutamate moiety of up to 0.78 and furoate moiety of up to 0.87. The total DS values of the esters range between 1.45 and 1.48 (Heinze et al., 2007). A xylan ibuprofen ester with a DS of 0.79 could be obtained with a molar ratio of 1–1 (AXU/ibuprofen imidazolide), whereas a DS of 1.24 can be achieved with a molar ratio of 1–2 (Daus & Heinze, 2010). The structural features of these xylan esters could be analyzed by ^{13}C NMR spectroscopy; the signals could be assigned to the corresponding carbons of the repeating units (Fig. 8).

The xylan esters were investigated according to their nanoparticle formation applying exchange of the solvent against water by dialysis. Whereas the xylan furoate pyroglutamates were dissolved in DMSO for dialysis, the xylan ibuprofen esters could be dissolved in DMA for nanoparticle formation. The nanoparticles formed gave a stable aqueous suspension and were analyzed regarding size and shape by DLS and SEM. The xylan furoate pyroglutamates provide nanospheres of small sizes, between 60 and 85 nm measured by DLS (Heinze et al., 2007). The xylan ibuprofen esters self-assemble into spherical nanoparticles with diameters ranging from 328 to 473 nm (Daus & Heinze, 2010). Figs. 9 and 10 show SEM imagines of nanoparticles of xylan esters. Freshly prepared nanoparticles were fixed on mica slides and investigated by SEM. The images of xylan furoate pyroglutamates obtained show that the particles have an almost spherical shape (Fig. 9a and b). After storing the suspensions for almost one year, the SEM images with higher resolution (Fig. 9c and d) point out that the particles stuck together.

As found for dextran nanoparticles (Hornig & Heinze, 2007), the exchange of DMSO against water is rather difficult, because traces of DMSO might be fixed in the core of the particles. By storing or drying, the DMSO may penetrate the surface, thus leading to partial “dissolution” of the particles surface. Consequently, they may stick together (Heinze et al., 2007). Otherwise after dialysis of xylan ibuprofen esters from DMA solution, SEM images presented in Fig. 9 clearly show that spherical particles could be obtained (Daus & Heinze, 2010). The nanoparticles of the xylan esters may be of interest for application in controlled drug release.

4. Conclusions

By chemical modification of xylan, manifold function could be introduced in the polymeric chain. The distribution of the function could be easily controlled by the activation conditions used especially by the synthesis of CMX and HPMAX. Depending on the DS and the distribution of the substituents, the xylan derivatives show differences in their properties, e.g., in the surface tension of the solutions. Hydrophobic xylan esters form spherical nanoparticles simply by applying a dialysis process. Based on structure–property-relationships, xylan derivatives possess an interesting spectrum of possible applications. They may be used as paper additive and flocculation aid, as antimicrobial agent in case of HPMAX or can be act as fibre modifying agent like XTMAB. They may act as polymeric tensides like methyl xylan and used as carrier of drugs (nanoparticles of xylan esters). Xylan sulphate may be applied as antiviral drugs and as blood coagulation inhibitor.

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References

Belmokaddem, F.-Z., Pinel, C., Huber, P., Petit-Conil, M., & Perez, D. D. S. (2011). Green synthesis of xylan hemicellulose esters. *Carbohydrate Research*, *346*, 2896–2904.
Bigand, V., Pinel, C., Perez, D. D. S., Rataboul, F., Huber, P., & Petit-Conil, M. (2011). Cationization of galactomannan and xylan hemicelluloses. *Carbohydrate Polymers*, *85*, 138–148.
Bratskaya, S., Schwarz, S., Laube, J., Liebert, T., Heinze, T., Krentz, O., et al. (2005). Effect of polyelectrolyte structural features on flocculation behavior: Cationic polysaccharides vs. synthetic polycations. *Macromolecular Materials and Engineering*, *290*, 778–785.
Bukovský, M., Kardosová, A., Koscova, H., & Kostálová, D. (1998). Immunomodulating activity of 4-O-methyl-D-glucurono-D-xylan from *Rudbeckia fulgida* var. sullivantii. *Biologia*, *53*, 771–775.
Christakopoulos, P., Katapodis, P., Kalogeris, E., Kekos, D., Macris, B. J., Stamatis, H., et al. (2003). Antimicrobial activity of acidic xylo-oligosaccharides produced by family 10 and 11 endoxylanases. *International Journal of Biological Macromolecules*, *31*, 171–175.
Crittenden, R. G., & Playne, M. J. (1996). Production, properties and applications of food-grade oligosaccharides. *Trends in Food Science and Technology*, *7*, 353–361.
Cunha, A., & Gandini, A. (2010). Turning polysaccharides into hydrophobic materials: A critical review. Part 2. Hemicelluloses, chitin/chitosan, starch, pectin and alginates. *Cellulose*, *17*, 1045–1065.
Daus, S. (2010). Wege zur nachhaltigen Nutzung von Hemicellulosen am Beispiel des Xylans. Ph.D. thesis, Friedrich Schiller University of Jena, Jena, Germany.
Daus, S., & Heinze, T. (2010). Xylan-based nanoparticles: Prodrugs for ibuprofen release. *Macromolecular Bioscience*, *10*, 211–220.
Daus, S., Petzold-Welcke, K., Kötteritzsch, M., Baumgaertel, A., Schubert, U. S., & Heinze, T. (2011). Homogeneous sulfation of xylan from different sources. *Macromolecular Materials and Engineering*, *296*, 551–561.
Ebringerová, A. (2005). Structural diversity and application potential of hemicelluloses. *Macromolecular Symposia*, *232*, 1–12.
Ebringerová, A., & Heinze, T. (2000). Xylan and xylan derivatives – biopolymers with valuable properties. 1. Naturally occurring xylans: Structures, isolation, procedure and properties. *Macromolecular Rapid Communications*, *21*, 542–556.
Gullón, P., Gonzallez-Munioz, M. J., van Gool, M. P., Schols, H. A., Hirsch, J., Ebringerova, A., et al. (2010). Production, refining, structural characterization and fermentability of rice husk xylooligosaccharides. *Journal of Agricultural and Food Chemistry*, *58*, 3632–3641.
Haack, V., Heinze, T., Schmidtke, M., Möllmann, U., Dahse, H.-M., & Härtl, A. (2002). DE 102 00 717.9, 10.01.2002, WO 2003057227.
Heinze, T., Petzold, K., & Hornig, S. (2007). Novel nanoparticles based on xylan. *Cellulose Chemistry and Technology*, *41*, 13–18.
Heinze, T., Liebert, T., & Koschella, A. (2006). *Esterification of polysaccharides*. Berlin, Heidelberg, New York: Springer., p. 86.
Heinze, T., Koschella, A., & Ebringerova, A. (2004). Chemical functionalization of xylan: A short review. In P. Gatenholm, & M. Tenkanen (Eds.), *Hemicelluloses: Science and technology. ACS symposium series*, Vol. 864 (pp. 312–325).
Heinze, T., Erler, U., Nehls, I., & Klemm, D. (1994). Determination of the substituent pattern of heterogeneously and homogeneously synthesized carboxymethyl cellulose using high-performance liquid chromatography. *Angewandte Makromolekulare Chemie*, *215*, 93–106.
Heinze, U., Heinze, T., & Klemm, D. (1999). Synthesis and structure characterization of 2,3-O-carboxymethylcellulose. *Macromolecular Chemistry and Physics*, *200*, 896–902.

Hornig, S., & Heinze, T. (2007). Nanoscale structures of dextran esters. *Carbohydrate Polymers*, *68*, 280–286.
Köhnke, T., Brelid, H., & Westman, G. (2009). Adsorption of cationized barley husk xylan on kraft pulp fibres: Influence of degree of cationization on adsorption characteristics. *Cellulose*, *16*(6), 1109–1121.
Linder, A., Bergman, R., Bodin, A., & Gatenholm, P. (2003). Mechanism of assembly of xylan onto cellulose surfaces. *Langmuir*, *19*(12), 5072–5077.
Lloyd, L. L., Kennedy, J. F., Methacanon, P., Paterson, M., & Knill, C. J. (1998). Carbohydrate polymers as wound management aids. *Carbohydrate Polymers*, *37*, 315–322.
Miraftab, M., Qiao, Q., Kennedy, J. F., Anand, S. C., & Groocock, M. R. (2003). Fibres for wound dressings based on mixed carbohydrate polymer fibres. *Carbohydrate Polymers*, *53*, 225–231.
Moure, A., Gullón, P., Dominguez, H., & Parajo, J. C. (2006). Advances in the manufacture, purification and applications of xylo-oligosaccharides as food additives and nutraceuticals. *Process Biochemistry*, *41*, 1913–1923.
Peng, X.-W., Ren, J.-L., Zhong, L.-X., & Sun, R.-C. (2012). Synthesis and characterization of amphoteric xylan-type hemicelluloses by microwave irradiation. *Journal of Agricultural and Food Chemistry*, *60*, 1695–1702.
Peng, X.-W., Ren, J.-L., & Sun, R.-C. (2010). Homogeneous esterification of xylan rich hemicelluloses with maleic anhydride in ionic liquid. *Biomacromolecules*, *11*, 3519–3524.
Petzold, K., Günther, W., Kötteritzsch, M., & Heinze, T. (2008). Synthesis and characterization of methyl xylan. *Carbohydrate Polymers*, *74*, 327–332.
Petzold, K., Schwikal, K., & Heinze, T. (2006). Carboxymethyl xylan – Synthesis and detailed structure characterization. *Carbohydrate Polymers*, *64*, 292–298.
Petzold, K., Schwikal, K., Günther, W., & Heinze, T. (2006). Carboxymethyl xylan – Control of properties by synthesis. *Macromolecular Symposia*, *232*, 27–36.
Rejane, C. G., de Britto, D., & Assis, O. B. G. (2009). A review of the antimicrobial activity of chitosan. *Polímeros: Ciência e Tecnologia*, *19*, 241–247.
Samuelsen, A. B., Lund, I., Djahromi, J. M., Paulsen, B. S., Wold, J. K., & Knutsen, S. H. (1999). Structural features and anti-complementary activity of some heteroxylan polysaccharide fractions from the seeds of Plantago major L. *Carbohydrate Polymers*, *38*, 133–143.
Schönberg, C., Oksanen, T., Suurnäkki, A., Kettunen, H., & Buchert, J. (2001). The importance of xylan for the strength properties of spruce kraft pulp fibres. *Holzforschung*, *55*, 639–644.
Schwikal, K. (2007). *Neue Funktionspolymere aus Xylan*. Uelvesbüll: Der Andere Verlag.
Schwikal, K., & Heinze, T. (2007). Dialkylaminoethyl xylans: Polysaccharide ethers with pH-sensitive solubility. *Polymer Bulletin*, *59*, 161–167.
Schwikal, K., Heinze, T., Saake, B., Puls, J., Kaya, A., & Esker, A. R. (2011). Properties of spruce sulfite pulp and birch kraft pulp after sorption of cationic birch xylan. *Cellulose*, *18*, 727–737.
Schwikal, K., Heinze, T., Ebringerová, A., & Petzold, K. (2006). Cationic xylan derivatives with high degree of functionalization. *Macromolecular Symposia*, *232*, 49–56.
Simkovic, I., Gedeon, O., Uhliarikova, I., Mendichi, R., & Kirschnerova, S. (2011). Xylan sulphate films. *Carbohydrate Polymers*, *86*, 214–218.
Söderqvist Lindblad, M., & Albertsson, A.-C. (2004). Chemical modification of hemicelluloses and gums. In S. Dumitriu (Ed.), *Polysaccharides: Structural diversity and functional versatility* (2nd ed., pp. 491–508). New York: Marcel Dekker.
Spiridon, I., & Popa, V. I. (2008). Hemicelluloses: Major sources, properties and applications. In M. N. Belgacem, & A. Gandini (Eds.), *Monomers, polymers and composites from renewable resources* (pp. 289–304). Amsterdam: Elsevier.
Vega, B., Petzold-Welcke, K., Fardim, P., & Heinze, T. (2012). Studies on the fibre surfaces modified with xylan polyelectrolytes. *Carbohydrate Polymers*, *89*, 768–776.