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Physical characterisation of the rhamnogalacturonan and homogalacturonan fractions of sugar beet (*Beta vulgaris*) pectin

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ABSTRACT

Acid extracted sugar beet (*Beta vulgaris*) pectin was subjected to enzymatic hydrolysis using fungal pectin methyl esterase (f-PME) and two endopolygalacturonanases (PGs I and II). From the hydrolysate, the RG-I fraction was separated and purified by chromatographic techniques. This RG-I fraction was shown to be of high weight average molar mass (188,000 g/mol), but low intrinsic viscosity (36 ml/g), which is consistent with a random coil conformation (L_p = 1.4 nm).

The HG fraction was prepared by mild acid hydrolysis of acid extracted pectin. The HG fraction was found to have a relatively low weight average molar mass (20,000 g/mol), but a rather high intrinsic viscosity (77 ml/g), which is consistent with the HG fraction being rigid in solution (L_p = 9.8 nm).

Lower molar mass pectins are richer in HG regions and pectins of higher molar mass are richer in RG-I regions. We conclude that the degradation of the HG region has an important impact on intrinsic viscosity, but less on molar mass and the inverse is true for the degradation of RG-I region. This has important consequences in terms of the functionality of sugar beet pectin molecules.

1. Introduction

Pectins are a complex family of heteropolysaccharides that constitute a large proportion of the primary cell walls of dicotyledons and play important roles in growth, development and senescence (Ridley, O'Neill, & Mohnen, 2001; Willats, McCartney, Mackie, & Knox, 2001). Pectic polysaccharides are made of several structural elements, the important of which are the homogalacturonan (HG) and type I rhamnogalacturonan (RG-I) regions often described in simplified terms as the "smooth" and "hairy" regions respectively. The HG region is composed of (1→4) linked α-D-Gal*p*A residues that can be partially methylated at *C*-6 (Pilnik & Voragen, 1970) and possibly partially acetyl-esterified at *O*-2 and/or *O*-3 (Rombouts & Thibault, 1986). The degree of methylation (DM) and the degree of acetylation (DAc) are defined as the number of moles of methanol or acetic acid per 100 moles of GalA. The degree of methylation in native pectins is generally in the order of DM ≈ 70–80, whereas degree of acetylation is generally much lower e.g. DAc ≈ 35 for sugar beet pectins (Rombouts & Thibault, 1986). The RG-I region consists of disaccharide repeating unit [→4)-α-D-Gal*p*A-(1→2)-α-L-Rha*p*-(1→]$_n$ with a variety of side chains consisting of L-arbinosyl and D-galactosyl residues (Voragen, Pilnik, Thibault, Axelos, & Renard, 1995). It has been reported that GalA residues in the RG-I region are partially acetylated (Ishii, 1997; Perrone et al., 2002) but not methylated (Komalavilas & Mort, 1989; Perrone et al., 2002). In the case of sugar beet pectin, the neutral side chain sugars are substituted with ferulic acid (Fry, 1982; Rombouts & Thibault, 1986) and there is evidence indicating that pectin chains can be dimerised via diferulic bridges (Levigne, Ralet, Quéméner, & Thibault, 2004; Levigne, Ralet, Quéméner, Thibault, Lapierre et al., 2004; Ralet, Cabrera et al., 2005). There are a number of different ways in which ferulic acid can dimerise the most common being: 5-5′; 8-O-4′; 8-5′ cyclic and 8-5′ non-cyclic dimers (Micard, Grabber, Ralph, Renard, & Thibault, 1997).

In order to characterise the physical and chemical properties of the type I rhamnogalacturonan region it is necessary to degrade the homogalacturonan region. This can be achieved in a controlled manner using polygalacturonanses (PGs). PGs catalyse the hydrolytic cleavage of the O-glycosyl bond of α-D-(1→4) polygalacturonate. This degradation proceeds in either a random (*endo*-PG, E.C. 3.2.1.15) or a terminal (*exo*-PG, E.C. 3.2.1.67) fashion. A large number of fungal PGs have been purified and characterised and although they appear to have similar amino acid compositions

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(Mohamed, Christensen, & Mikkelsen, 2003) they have different chemical and physical properties. *Aspergillus niger* has been shown to posses at least seven *endo*-PGs (Benen, van Alebeek, Voragen, & Visser, 2003). Both methyl and acetyl groups have been shown to affect the mode of action of *endo*-PGs (Mohamed et al., 2003; Renard & Jarvis, 1999a,b).

In the present study, two different *endo*-PGs were used in conjunction with a fungal pectin methyl esterase (f-PME) to generate the RG-I region of sugar beet pectin. The enzyme hydrolysate was fractionated by anion exchange and size exclusion chromatography and the physical and chemical properties of the resultant RG-1 fragment was characterised.

The homogalacturonan (HG) region was generated by mild acid hydrolysis of sugar beet pectin after saponification with sodium hydroxide at 4 °C in order to prevent β-elimination. The physical characteristics of the HG region were measured without any further purification.

2. Experimental

2.1. Materials

2.1.1. Enzymes

Recombinant fungal pectin methyl esterase from *A. aculeatus* (f-PME, E.C. 3.1.1.11, UniProt Q12535) and endopolygalacturonase I and II from *A. niger* (PG I and PG II, E.C. 3.2.1.15, UniProt P26213 and P26214) were provided by Novozymes (Bagsvaerd, Denmark). The purification of PGI and PGII are described in detail in Ralet, Crépeau and Bonnin (2008) and Bonnin, Le Goff, et al. (2002), respectively.

2.2. Methods

2.2.1. Acid extraction of sugar beet pulp (Pectin A)

The alcohol insoluble residue (AIR) (5 g) from sugar beet pulp was obtained as described in Levigne, Ralet, and Thibault (2002) in brief sugar beet roots were immersed in 3 l of boiling ethanol (96%) and the slurry was filtered through G3 sintered glass and the insoluble material was repeatedly suspended in 70% ethanol until the filtrate gave a negative reaction to the phenol–sulphuric acid assay (Dubois, Gilles, Hamilton, Rebers, & Smith, 1956). The resultant AIR was then dispersed in 150 ml HCl at pH 1.0 and heated for 30 min at 75 °C with agitation. The residue was separated through G3 sintered glass. The supernatant was adjusted to pH 4.5 with 2 M NaOH, concentrated under vacuum at 40 °C, extensively dialysed against distilled water and freeze-dried at condenser temperature of −55 °C and a pressure of 4 mbar (400 Pa) for 48 h. The resultant pectin (yield 280 mg/g) will be referred to as pectin A. The RG-I and HG fractions of pectin A will be prepared by enzymatic and acid hydrolysis, respectively and characterised in terms of molar mass, intrinsic viscosity and confirmation after purification where appropriate (see Fig. 1).

2.2.2. Mild acid hydrolysis of pectin A

Pectin A (50 mg) was dissolved in distilled water at approximately 10 mg/ml and the pH was increased to pH 12 by the addition of 0.2 M NaOH. The mixture was incubated for 24 h at 4 °C, after which the pH was lowered to pH 1 on addition of 2.5 M HCl. The resultant mixture was heated at 80 °C for 72 h, during which a precipitate was formed. This precipitate has previously been shown to be the homogalacturonan region (Thibault, Renard, Axelos, Roger, & Crépeau, 1993). The precipitate (AHCl72) was separated by centrifugation and resolubilised by neutralisation with sodium hydroxide (1 M) prior to analysis by HPSEC.

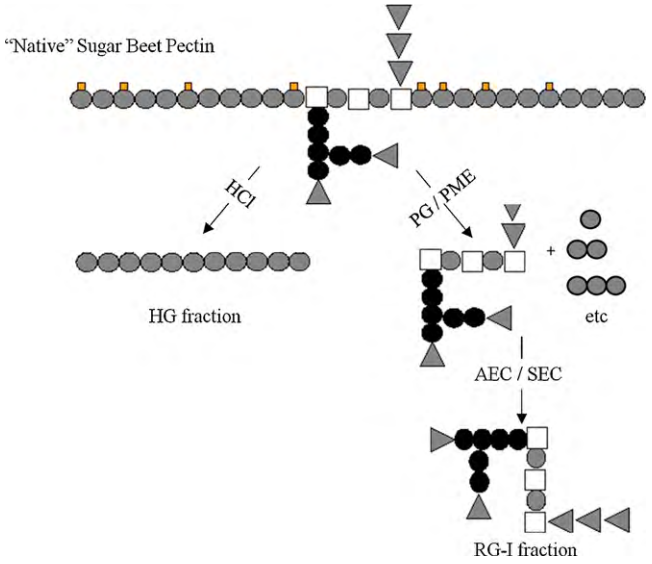

Fig. 1. Schematic structure for generalised sugar beet pectin: galacturonic acid (●); galactose (●); arabinose (▼); rhamnose (□); and methyl groups (■). Adapted from Perez, Rodríguez-Carvajal, and Doco (2003). PG, endopolygalacturonase I and II from *A. niger*; PME, fungal pectin methyl esterase from *A. aculeatus*; AEC, anion exchange chromatography; SEC, size exclusion chromatography.

2.2.3. Enzymatic hydrolysis of pectin A

Sugar beet pectin A (100 mg) was dissolved in 0.05 M sodium succinate buffer pH 4.5 at a concentration of 7.5 mg/ml overnight at 30 °C with gentle agitation. The pectin solution was mixed with an enzymatic solution (in 0.05 M succinate buffer pH 4.5) containing f-PME, PG I and PG II. Enzymes were present 25.7, 2.1 and 2.1 nkat/ml respectively in the final reaction mixture. The reaction mixture containing 4.3 mg pectin/ml was incubated at 30 °C for 24 h.

2.2.4. Analytical

Galacturonic acid and neutral sugar (expressed arbitrarily as arabinose) contents were determined in triplicate by the automated m-hydroxbiphenyl (Thibault, 1979) and orcinol methods (Tollier & Robin, 1979), respectively, the latter being corrected for interfering galacturonic acid.

Individual neutral sugars were obtained by hydrolysis with 2 M trifluoroacetic acid at 121 °C for 2 h and converted to their corresponding alditol acetates (Blakeney, Harris, Henry, & Stone, 1983). These alditol acetates were subsequently analysed by gas chromatography using myo-inositol (0.5 mg) as an internal standard on a DB-225 fused-silica capillary (30 m × 0.32 mm i.d.) column (J&W Scientific, Courtaboeuf, France) mounted in a DI 200 chromatograph (Delsi Nermag Instruments, Argenteuil, France) with hydrogen as the carrier gas at a constant temperature of 220 °C.

Phenolic acids were determined by HPLC after saponification and extraction. Pectin A (8.1 mg) was dissolved in 1 ml of 2 M NaOH and saponified under argon for 30 min at 35 °C in the dark. The internal standard (*o*-coumaric acid) was added, prior to neutralisation with 2 M HCl and the extraction of the phenolic compounds into ether. The ether phase was evaporated and the residue dissolved in 50/50 water/methanol. 20 μl of this material was injected onto a Purospher C18 column (Merck, Darmstadt, Germany) and a gradient elution was performed using acetonitrile (A) and pH 4.6 sodium acetate buffer (B) at 60 ml/h and 30 °C: (0 min, $A = 15\%$; 6 min, $A = 15\%$; 26 min, $A = 35\%$; 26.5 min, $A = 60\%$; 30.5 min, $A = 60\%$; 31 min, $A = 15\%$; 35 min, $A = 15\%$). The eluent was detected at 320 nm. Response factors were determined relative to *o*-coumaric acid (ferulic acid = 0.57 and for the diferulic acids 5-

Table 1
Chemical composition of pectin A and its RG-I fraction.

Sample	Sugar composition (mol%)			Ferulic acid content (%)[a]
	Gal A	Rha	Other neutral sugars	
Pectin A[b]	68.6	8.4	22.2	0.8
APG24F1 (Pectin A neutral sugar fraction)	n.d.	n.d.	99	2.0
APG24F10a (RG-I fraction)	21.9	16.7	61.5	2.4

Note: For the chemical composition of low molecular weight enzymatic hydrolysis products (APG24F2–APG24F9), see Ralet et al. (2005a).
[a] $\%FA = 100\% \times (UV_{calculated\ mass}/RI_{calculated\ mass})$.
[b] Does not include the peak shown to consist almost entirely (99%) of neutral sugars i.e. APG24F1 after anion exchange chromatography.

5′ = 0.50; 8-O-4′ = 1.04; 8-5′ cyclic dimer = 1.09 and 8-5′ non-cyclic dimer = 0.90).

2.2.5. Physical

High performance size exclusion chromatography (HPSEC) was performed at room temperature on a system consisting of a Shodex OH SB-G guard column (Showa Denko, Tokyo, Japan) followed by in series (Shodex OH-Pak SB-805 HQ and Shodex OH-Pak SB-804 HQ) eluted with 50 mM sodium nitrate buffer containing 0.02% sodium azide as an antibacterial agent at a flow rate of 42 ml/h. The eluent was detected on-line by:

(i) SpectroMonitor 3000 variable wavelength UV detector at 325 nm (LDC/Milton Roy, Paris, France).
(ii) MiniDawn light scattering (LS) detector (Wyatt, Santa Barbara, U.S.A.).
(iii) T-50A differential pressure viscometer (DPV) (Viscotek, Huston, U.S.A.).
(iv) ERC 7515A differential refractometer (RI) (Sopares, Gentilly, France).

Weight average molar masses were calculated using ASTRA (Wyatt, Santa Barbara, U.S.A.) and weight intrinsic viscosities using the TRISEC (Viscotek, Huston, U.S.A.). *dn*/*dc* was taken to be 0.146 ml/g (Chapman, Morris, Selvendran, & O'Neill, 1987; Levigne et al., 2002; Morris, Foster, & Harding, 2000; Morris et al., 2008) for pectin A and its HG and RG-I fractions.

2.2.6. Anion exchange chromatography (AEC)

Anion exchange chromatography was performed in order to purify the RG-I fraction on a DEAE-Sepharose CL 6B (Pharmacia) column (30 cm × 2.6 cm) equilibrated with degassed 0.05 M sodium succinate buffer pH 4.5 at a flow rate of 90 ml/h at room temperature. The hydrolysis products of pectin A after 24 h incubation with polygalacturonase (APG24) (25 ml) were loaded onto the column and the gel was washed with 400 ml of 0.05 M sodium succinate buffer. The bound material was eluted with a linear NaCl gradient 0 → 0.4 M NaCl in 0.05 M sodium succinate buffer, 1660 ml. Sodium succinate buffer containing 0.4 M NaCl (400 ml) was then applied. Fractions (9 ml) were collected and analysed for their galacturonic acid and neutral sugar contents. Fractions (F1–F10) were combined and concentrated by in vacuum rotary evaporation at 40 °C.

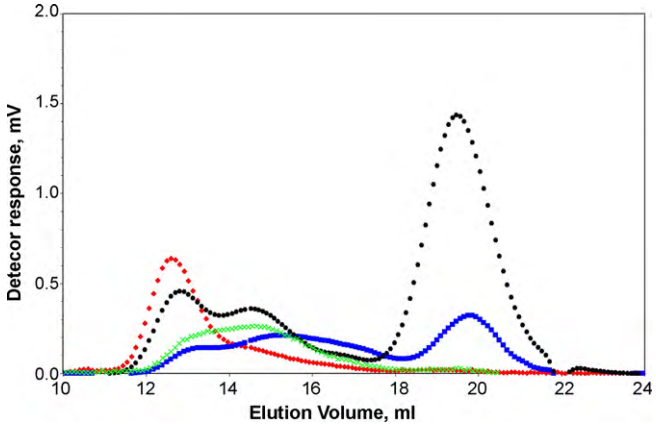

Fig. 2. Multi-detector HPSEC chromatogram for pectin A: LS 90° (♦), RI (■), UV 325 nm (●) and DPV (×). *Note*: The LS 90° and DPV signals have been multiplied by 5 to improve visualisation.

2.2.7. Preparative size exclusion chromatography (SEC)

Size exclusion chromatography was performed at room temperature on a Sephacryl S-200 column (60 cm × 1.6 cm) equilibrated with degassed 0.05 M sodium succinate buffer pH 4.5. The anion exchange chromatography fraction containing the RG-I component: APGF10 (1.5 ml) was loaded and eluted at a flow rate of 25 ml/h; 1.5 ml fractions were collected and analysed for their galacturonic acid and neutral sugar contents. Appropriate fractions were combined and concentrated by in vacuum rotary evaporation at 40 °C.

3. Results and discussion

3.1. Physico-chemical characterisation of pectin A

Pectin A was first characterised/analysed by HPSEC. The peak at ~19 ml (Fig. 2) is shown to consist entirely of neutral sugars (99%) see Section 3.3 (Table 1). This "component" is "free" from the main pectic chain and constitutes neutral sugar side chains, which were cleaved from the main pectin chain during acid extraction, but are of sufficiently large molar mass to remain after dialysis. Therefore this component has been ignored when calculating the physical and chemical properties of pectin A.

Table 2
Physical and conformational properties of sugar beet pectin A and its HG and RG-I fractions. Values for a "typical" low methoxyl citrus pectin (P_{19}) are shown for comparison[a].

Sample	M_w (g/mol)	$[\eta]_w$ (ml/g)	M_L (g/(mol nm))	L_p (nm)	L_p/M_L (nm² mol/g)
A[b]	286,000	285	620	7.3	0.0118
RG-I	188,000	36	555	1.4	0.0025
HG	20,000	77	395	9.8	0.0248
P_{19}	165,000	395	330	10.0	0.0303

[a] From Morris et al. (2008).
[b] Does not included the peak shown to consist entirely of neutral sugars i.e. APG24F1 after anion exchange chromatography.

Pectin A exhibits a typical distribution of sugars (Table 1), although the amount of total neutral sugars compared to value calculated by Levigne et al. (2002) appears to be a lot lower due to the removal of the contribution of the "free" neutral sugar side chains.

Acid extracted pectin is heterogeneous with respect to molar mass, intrinsic viscosity and composition (Tables 1 and 2 and Fig. 2). The use of UV absorbance (325 nm) allows the visualisation of those populations of pectic molecules (or constituents), which are substituted with ferulic acid i.e. the arabinan, galactan or arabinogalactan side chains present on the RG-I region of sugar beet pectin. We can see from the differences between the RI and UV profiles that there are distinct populations of pectic molecules; the components eluting at the lowest elution volumes (12–14 ml) appear to be richer in ferulic acid than the species, which elute between 14 and 18 ml and should therefore also be richer in neutral sugars. We propose that this neutral sugar/ferulic acid rich component is the result of dimerisation of pectins via diferulic bridges. Diferulic acids are known to be present in this pectin sample (11% of total ferulic acids) and have recently been shown to bridge arabinose residues of Driselase degraded sugar beet pectin (Levigne, Ralet, Quéméner, & Thibault, 2004) and to have peripheral locations on pectin hairy regions (Levigne, Ralet, Quéméner, Thibault, Lapierre et al., 2004).

UV detection also allows a global estimate of the total % of ferulic acid in pectin A, which was found to be 0.8% (Table 1), and is in good agreement with the value of 0.7% found from C18 HPLC after saponification and organic extraction. As ferulic acid only forms ester-linkages with the neutral sugar side chains of the RG-I region, therefore an increase in the % of ferulic acid is therefore the result of a loss of galacturonic acid and can be used as an indication of the purity of the RG-I region.

3.2. Enzymatic hydrolysis of pectin A

After 24 h of enzymatic hydrolysis of pectin A by PG and PME, the weight average molar mass and weight average intrinsic viscosity were reduced considerably as can be seen by the loss of higher molecular weight material; this is consistent with previous estimates (Oosterveld, Beldman, & Voragen, 2002) and was confirmed after purification (Table 1). As can be seen the peak at 19 ml is unaffected by enzymatic hydrolysis by PG and PME; this is consistent with this being a fragment of a neutral sugar side chain and being free of GalA (Fig. 3). Furthermore 100% of the ferulic acid substituted material is conserved in the pectic fragment at 16–17 ml (excluding the peak at 19 ml) and the amount of ferulic acid has increased to 2.4%. This is consistent with the purification of the RG-I region of sugar beet pectin, as this is the result of the loss of galacturonic acid and therefore concentration of neutral sugars.

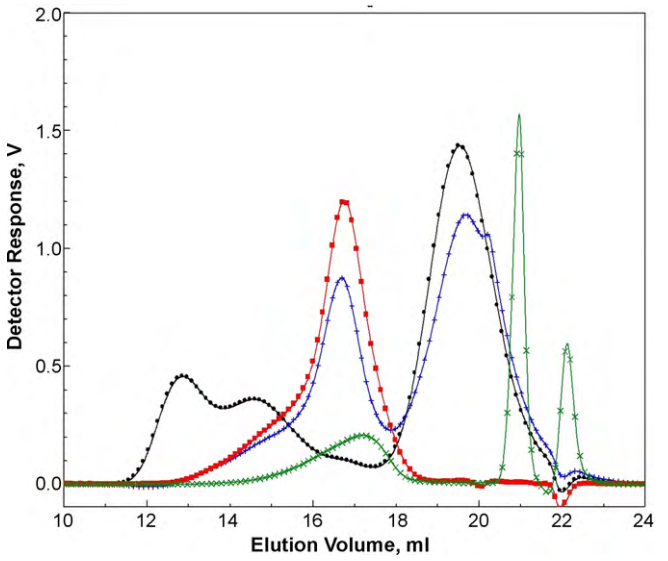

Fig. 3. HPSEC chromatogram for Pectin A (●), APG24 (+), APG24F10a (■) and AHCl72 (×). *Note*: The chromatogram for AHCl72 is an RI trace; all others are UV absorbance at 325 nm. AHCl72 contains no ferulic acid and therefore shows no UV signal at 325 nm.

It is however difficult to calculate the molar masses of the RG-I fragment using light scattering due to the presence of galacturonic acid oligomers (Ralet, André-Leroux, Quéméner, & Thibault, 2005) contributing to the light scattering (LS), refractive index (RI) and differential pressure viscometer (DPV) signals (but not the UV signal), therefore a better estimate of the molar mass and intrinsic viscos-

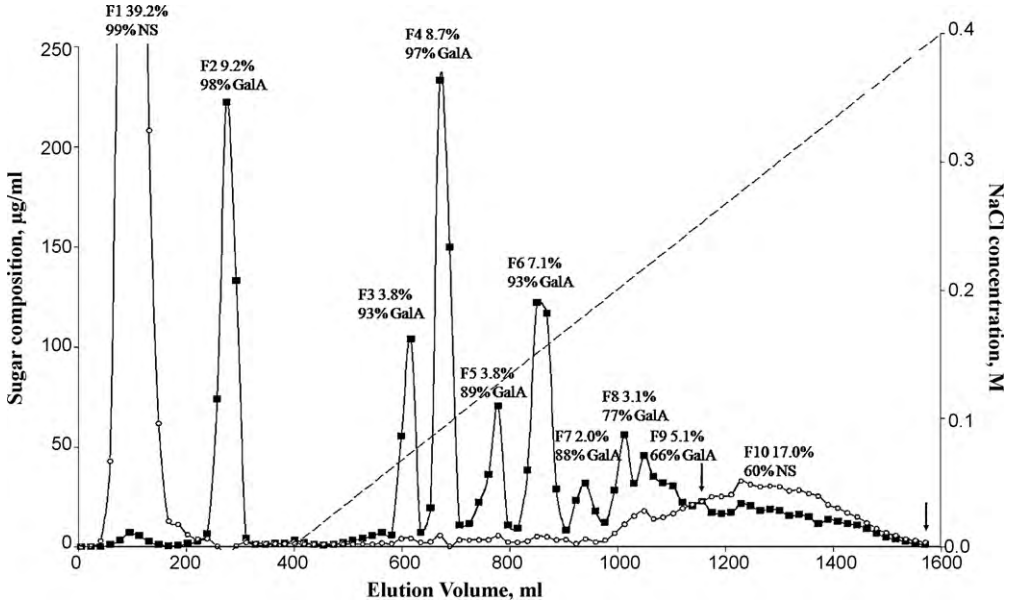

Fig. 4. Anion exchange chromatogram (DEAE-Sepharose CL 6B) for pectin A after enzymatic hydrolysis for 24 h at 30 °C with f-PME, PGs I and II (■ Gal A; ○, neutral sugars). The proportion of each fraction present is indicated, together with the major constituent: galacturonic acid (GalA) or total neutral sugars (NS). Fraction APGF10 which will be further purified by SEC is indicated by the arrows.

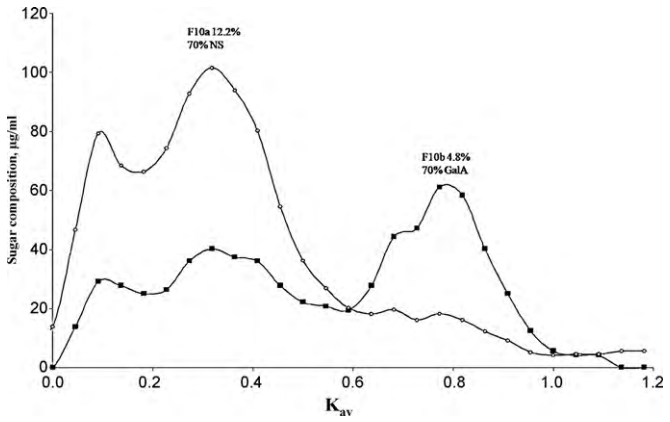

Fig. 5. Size exclusion chromatogram (Sephacryl S-200) for APGF10 (■ Gal A; ○, neutral sugars). The proportion of each fraction present is indicated, together with the major constituent: galacturonic acid (GalA) or total neutral sugars (NS).

ity can be made after chromatographic separation on a preparative scale. This will also allow chemical analyses.

3.3. Anion exchange chromatography (AEC)

After AEC it can be seen (Fig. 4) that there are 10 components most of which (F2–F9) are oligogalacturonides of various DPs (1–10), DMs and DAcs (see Ralet, Cabrera et al., 2005 for a full characterisation). The unbound fraction (F1) is the neutral sugar fraction (99%) described earlier. The fraction, which is retained the longest (F10) is richer in neutral sugars and is presumed to be the RG-I fraction, although it has been shown previously (Ralet, Cabrera et al., 2005) that this fraction also contains larger oligogalacturonides.

3.4. Preparative size exclusion chromatography (SEC)

This fraction (F10) was subjected to SEC on Sephacryl S-200 (Fig. 5) and two sub-fractions (F10a and F10b) were separated. The higher molecular weight the sub-fraction (F10a) originates from the RG-I region and the lower molecular weight sub-fraction consists of oligogalacturonides (Ralet, Cabrera et al., 2005). Fraction F10a which has not previously been examined in detail, was dialysed, freeze-dried and physico-chemical properties characterised.

3.5. Physico-chemical characterisation of RG-I fraction (APG24F10a)

The RG-I region was found to contain 22 mol% GalA, 17 mol% Rha and 62 mol% neutral sugars (GalA:Rha:NS ratio of 1.3:1.0:3.6) suggesting that this fraction is indeed the RG-I region and the HG component has been almost entirely degraded; this was also supported by a further increase in the amount of ferulic acid to 2.4%, which is 3 times that present in pectin A and is slightly larger than the increase in total neutral sugars ~2.6 times (Table 1). This fraction was found to have a weight average molar mass of 188,000 g/mol and the weight average intrinsic viscosity is 36 ml/g (Table 2), which is relatively low for a molecule of this molar mass and is reflective of a highly compact or random coil conformation. This value is much higher than previous estimates of 50,000 g/mol (Oosterveld et al., 2002) and 12,000 g/mol (Guillon & Thibault, 1990) calculated from light scattering and viscosity measurements respectively, but it should be noted that in both cases the values are likely to be underestimated due to the presence of contaminants e.g. galacturonic acid oligomers, salts and enzymes. In our case the weight average molar mass of RG-I is greatly influenced by presence of "aggregates" appearing as shoulders on the UV chromatogram at 13–14 and 14–15 ml (Fig. 3), the exact nature of these aggregates is not clear, but we believe that any diferulic bridges present in the pectin A would also be present in the purified RG-I region as enzymatic hydrolysis and chromatographic separation appear to have no affect on ferulic acid residues. Another factor influencing the molar mass is that at least some of the lower molar mass RG-I molecules may have co-eluted with the larger oligogalacturonides during SEC fractionation.

3.6. Physical characterisation of HG fraction (AHCl72)

During 72 h acid hydrolysis of pectin A at 80 °C a precipitate is formed (~98% GalA) this is consistent with previous measurements (Thibault et al., 1993). After neutralisation both the insoluble and soluble fractions were characterised by HPSEC. The soluble fraction did not consist of any polymeric material; all components eluted near the total volume (results not shown) and probably contained fragments of neutral sugar side chains. The insoluble fraction also contains low molar mass material eluting near the total volume and represent the salts formed after neutralisation. There is however a polymeric component with a peak at an elution volume at ~17 ml (× in Fig. 3). This component was found to have a weight average molar mass of 20,000 g/mol (Table 2). This value is in good agreement with the values of 17,000–21,000 g/mol estimated previously for an acid hydrolysed beet pectin HG region (Hellin, Ralet, Bonnin, & Thibault, 2005; Ralet, Crépeau, Lefebvre et al., 2008; Thibault et al., 1993; Yapo, Lerouge, Thibault, & Ralet, 2007) and slightly higher than the estimated molar mass of 16,000 g/mol for an enzymatically hydrolysed sugar beet pectin HG region (Bonnin, Dolo, Le Goff, & Thibault, 2002). The weight average intrinsic viscosity of 77 ml/g (Table 2) is again in general agreement with value found previously (75–92 ml/g) for the homogalacturonan region of pectins (Ralet, Crépeau, Lefebvre et al., 2008; Thibault et al., 1993; Yapo et al., 2007).

3.7. Conformational analysis

3.7.1. Global analysis method (HYDFIT)

The linear flexibility of polymer chains can also be represented quantitatively in terms of the persistence length, L_p of equivalent *worm-like chains* (Kratky & Porod, 1949) where the persistence length is defined as the average projection length along the initial direction of the polymer chain. In the case of a theoretical perfect random coil $L_p = 0$ and for the equivalent extra-rigid rod (Harding, 1997) $L_p = \infty$, although in practice limits of ~1 nm for random coils (e.g. pullulan) and 200 nm for a extra-rigid rod (e.g. DNA) are more appropriate (Tombs & Harding, 1998).

The persistence length, L_p and mass per unit length, M_L can be estimated using Multi-HYDFIT program (Ortega & García de la Torre, 2007) which considers data sets of intrinsic viscosity and molar mass. It then performs a minimisation procedure (see Ortega & García de la Torre, 2007) finding the best values of M_L and L_p satisfying the Bushin–Bohdanecky (Bohdanecky, 1983; Bushin, Tsvetkov, Lysenko, & Emel'yanov, 1981) equation (Eq. (1)).

$$\left(\frac{M_w^2}{[\eta]}\right)^{1/3} = A_0 M_L \Phi^{-1/3} + B_0 \Phi^{-1/3} \left(\frac{2L_p}{M_L}\right)^{-1/2} M_w^{1/2} \quad (1)$$

and

$$M_L = \frac{m}{l} \quad (2)$$

m and l are the average molar mass and length of the average monomeric unit.

From Fig. 6A–C and Table 2 we can see that the persistence lengths for pectin A and the HG fraction are larger than that of the RG-I fraction. This would suggest a random coil conformation

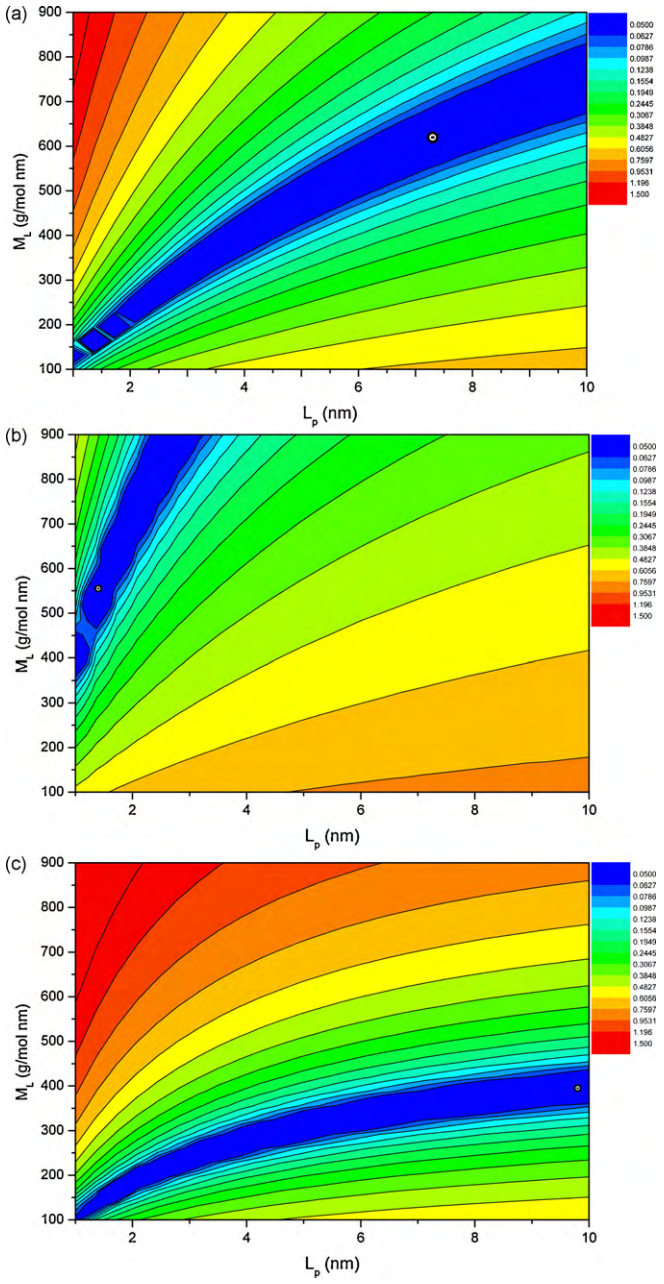

Fig. 6. Solutions to the Bushin–Bohdanecky using the HYDFIT algorithm (Ortega and García de la Torre, 2007). The *x*-axis and *y*-axis represent L_p (nm) and M_L (g/mol nm) respectively. The target function, Δ is calculated over a range of values for M_L and L_p. In these representations, the values of Δ function are represented by the full colour spectrum, from the minimum in the target function in blue ($\Delta = 0.5$) to red ($\Delta \geq 1.5$). The calculated minima are indicated (⊙). (A) Pectin A ($L_p = 7.3$ nm and $M_L = 620$ g/mol nm); (B) RG-I fraction ($L_p = 1.4$ nm and $M_L = 555$ g/mol nm); (C) HG fraction ($L_p = 9.8$ nm and $M_L = 395$ g/mol nm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

for the RG-I region and a less flexible conformation for both pectin A and HG regions. These results are consistent with previous findings which suggest that sugar beet, apple and flax pectins have flexible structures (Axelos & Thibault, 1991; Cros, Garnier, Axelos, Imbery, & Perez, 1996; Ralet, Crépeau, Lefebvre et al., 2008) and that HG-rich regions (or pectins) are considerably stiffer (Braccini, Grasso, & Perez, 1999; Cros et al., 1996; Morris et al., 2008; Noto, Martorana, Bulone, & San Biagio, 2005). The values of the mass per unit lengths (Fig. 6A–C and Table 2) indicate that both sugar beet pectin A and the RG-I fraction are highly branched (hairy)

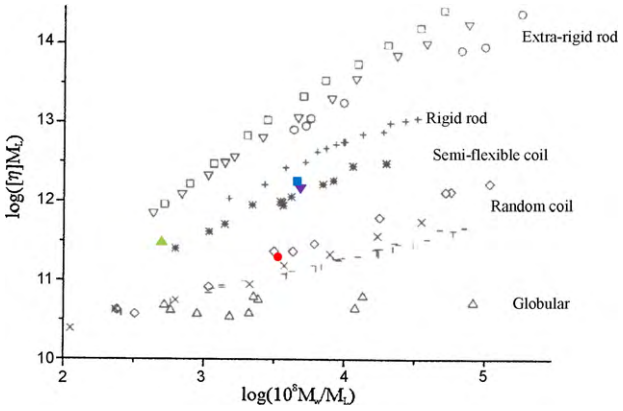

Fig. 7. Normalised scaling plot of $[\eta]M_L$ versus M_w/M_L (adapted from Pavlov et al., 1999) where the solution conformations for Pectin A (■) and its RG-I (●) and HG (▲) fractions are indicated a typical citrus pectin is shown for comparison (▽). All other symbols are as defined previously (Pavlov et al., 1999) in brief: schizophyllan (□), DNA (○), globular proteins (△), xanthan (▽), poly(1-vinyl-2-pyrrolidone) (◊), cellulose nitrate (+), pullulan (×), methyl cellulose (∗), poly-α-methylstyrene (−) and polystyrene (|).

and the HG region is essentially unbranched (smooth), although we would expect the value for the RG-I region to be higher than that of pectin A. Overall flexibility can be estimated from the ratio of L_p/M_L (nm^2 mol/g) which decreases with increasing flexibility (Patel et al., 2008). Therefore we can see that in terms of flexibility RG-I > pectin A > HG ≈ citrus pectin (Table 2).

3.7.2. *Conformation zoning (normalised scaling relations)*

Pavlov, Harding, and Rowe (1999) described a new procedure to represent the conformation of polymers in solution based on the relationship between their molar mass, intrinsic viscosity and mass per unit length, M_L. In this case we have taken the mass per unit length calculated previously using the HYDFIT algorithm (Ortega & García de la Torre, 2007). As we can see from Fig. 7 both pectin A and the HG fraction have conformations which fall in either the rigid rod or semi-flexible coil zones; this is in agreement with findings on citrus pectins (Morris et al., 2008) (*Note*: the high value of M_L for pectin A may lead to an overestimation of the rigidity). Whereas the RG-I region clearly adopts a random coil conformation, which is consistent with a persistence length of 1.4 nm (Tombs & Harding, 1998). This is again consistent with a more flexible structure for the RG-I fraction.

4. Conclusions

Acid extracted sugar beet pectin was shown to be heterogeneous in terms of composition and it is proposed that a high molar mass ferulic acid rich fraction may be the result of diferulic acid bridging between pectin molecules and more specifically between the RG-I regions of pectin molecules.

The enzymatic treatment of pectin A followed by AEC and SEC resulted in a RG-I fraction which was now free of the HG component. This RG-I fraction was shown to be of high weight average molar mass (188,000 g/mol), but low intrinsic viscosity (36 ml/g), which is consistent with a random coil conformation. This RG-1 fraction has a GalA:Rha ratio of 1.3:1.0 and is composed of almost 80% neutral sugars and 2.4% ferulic acid.

The HG fraction of acid extracted pectin was also characterised, although without further purification and was found, to have a relatively low weight average molar mass (20,000 g/mol), but a rather high intrinsic viscosity (77 ml/g), which is consistent with previous molar mass and intrinsic viscosity estimates (Bonnin, Dolo, et al., 2002; Ralet, Crépeau, Lefebvre et al., 2008; Thibault et al., 1993) and with the HG region being rigid in solution.

In general we can conclude that the degradation of the HG region(s) has an important impact on intrinsic viscosity, but less on molar mass and the inverse is true for the degradation of RG-I region.

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References

Axelos, M. A. V., & Thibault, J.-F. (1991). Influence of the substituents of the carboxyl groups and of the rhamnose content on the solution properties and flexibility of pectins. *International Journal of Biological Macromolecules*, *13*, 77–82.

Benen, J. A. E., van Alebeek, G. J. W. B., Voragen, A. G. J., & Visser, J. (2003). Mode of action analysis and structure—function relationships in *Aspergillus niger* enzymes. In A. G. J. Voragen, H. A. Schols, & R. Visser (Eds.), *Advances in pectin and pectinase research* (pp. 235–256). Dordrecht, The Netherlands: Kluwer Academic Press.

Blakeney, A. B., Harris, P. J., Henry, R. J., & Stone, B. A. (1983). A simple and rapid preparation of alditol acetates for monosaccharide analysis. *Carbohydrate Research*, *113*, 291–299.

Bohdanecky, M. (1983). New method for estimating the parameters of the worm-like chain model from the intrinsic viscosity of stiff-chain polymers. *Macromolecules*, *16*, 1483–1492.

Bonnin, E., Dolo, E., Le Goff, A., & Thibault, J.-F. (2002). Characterisation of pectin subunits released by an optimum combination of enzymes. *Carbohydrate Research*, *337*, 1687–1696.

Bonnin, E., Le Goff, A., Körner, R., Vigouroux, J., Roepstorff, P., & Thibault, J.-F. (2002). Hydrolysis of pectins with different degrees and patterns of methylation by the endopolygalacturonase from *Fusarium moniliforme*. *Biochimica et Biophysica Acta*, *1596*, 83–94.

Braccini, I., Grasso, R. P., & Perez, S. (1999). Conformational and configurational features of acidic polysaccharides and their interactions with calcium ions: A molecular modeling investigation. *Carbohydrate Research*, *317*, 119–130.

Bushin, S. V., Tsvetkov, V. N., Lysenko, Y. B., & Emel'yanov, V. N. (1981). Conformational properties and rigidity of molecules of ladder polyphenylsiloxane in solutions according the data of sedimentation-diffusion analysis and viscometry. *Vysokomolekulyarnye Soedineniya, Seriya A*, *23*, 2494–2503.

Chapman, H. D., Morris, V. J., Selvendran, R. R., & O'Neill, M. A. (1987). Static and dynamic light scattering studies of pectic polysaccharides from the middle lamellae and primary cell walls of cider apples. *Carbohydrate Research*, *165*, 53–68.

Cros, S. C., Garnier, C., Axelos, M. A. V., Imbery, A., & Perez, S. (1996). Solution conformations of pectin polysaccharides: Determination of chain characteristics by small angle neutron scattering, viscometry and molecular modeling. *Biopolymers*, *39*, 339–352.

Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A., & Smith, F. (1956). Colorimetric method for the determination of sugars and related substances. *Analytical Chemistry*, *28*, 350–356.

Fry, S. C. (1982). Phenolic compounds of the primary cell wall: Feruloylated disaccharides of D-galactose and L-arabinose from spinach polysaccharide. *Biochemical Journal*, *203*, 493–504.

Guillon, F., & Thibault, J.-F. (1990). Oxidative cross linking of chemically and enzymatically modified sugar beet pectin. *Carbohydrate Polymers*, *12*, 353–374.

Harding, S. E. (1997). The intrinsic viscosity of biological macromolecules. Progress in measurement, interpretation and application to structure in dilute solution. *Progress in Biophysics and Molecular Biology*, *68*, 207–262.

Hellin, P., Ralet, M.-C., Bonnin, E., & Thibault, J.-F. (2005). Homogalacturonans from lime pectins exhibit homogeneous charge density and molar mass distributions. *Carbohydrate Polymers*, *60*, 307–317.

Ishii, T. (1997). O-acetylated oligosaccharides from pectins of potato tuber cell walls. *Plant Physiology*, *113*, 1265–1272.

Komalavilas, P., & Mort, A. J. (1989). The acetylation of O-3 of galacturonic acid in the rhamnose-rich portion of pectin. *Carbohydrate Research*, *189*, 261–272.

Kratky, O., & Porod, G. (1949). Röntgenungtersuchung gelöster fadenmoleküle. *Recueil Des Travaux Chimiques Des Pays-Bas*, *68*, 1106–1109.

Levigne, S., Ralet, M.-C., Quéméner, B. C., Pollet, B. N.-L., Lapierre, C., & Thibault, J.-F. (2004). Isolation from sugar beet cell walls of arabinan oligosaccharides esterified by two ferulic acid monomers. *Plant Physiology*, *134*, 1173–1180.

Levigne, S., Ralet, M.-C., Quéméner, B. C., & Thibault, J.-F. (2004). Isolation of diferulic bridges ester-linked to arabinan in sugar beet cell walls. *Carbohydrate Research*, *339*, 2315–2319.

Levigne, S., Ralet, M.-C., & Thibault, J.-F. (2002). Characterisation of pectins extracted from fresh sugar beet under different conditions using an experimental design. *Carbohydrate Polymers*, *49*, 145–153.

Micard, V., Grabber, J. H., Ralph, J., Renard, C. M. C. G., & Thibault, J.-F. (1997). Dehydrodiferulic acids from sugar beet pulp. *Phytochemistry*, *44*, 1365–1368.

Mohamed, S. A., Christensen, T. M. I. E., & Mikkelsen, J. D. (2003). New polygalacturonanases from *Trichoderma reesei*: Characterisation and their specificities to partially methylated and acetylated pectins. *Carbohydrate Research*, *338*, 515–524.

Morris, G. A., Foster, T. J., & Harding, S. E. (2000). The effect of degree of esterification on the hydrodynamic properties of citrus pectin. *Food Hydrocolloids*, *14*, 764–767.

Morris, G. A., García de la Torre, J., Ortega, A., Castille, J., Smith, A., & Harding, S. E. (2008). Molecular flexibility of citrus pectins by combined sedimentation and viscosity analysis. *Food Hydrocolloids*, *22*, 1435–1442.

Noto, R., Martorana, V., Bulone, D., & San Biagio, B. L. (2005). Role of charges and solvent on the conformational properties of poly(galacturonic acid) chains: A molecular dynamics study. *Biomacromolecules*, *6*, 2555–2562.

Oosterveld, A., Beldman, G., & Voragen, A. G. J. (2002). Enzymic modification of pectic polysaccharides obtained from sugar beet pulp. *Carbohydrate Polymers*, *48*, 73–81.

Ortega, A., & García de la Torre, J. (2007). Equivalent radii and ratios of radii from solution properties as indicators of macromolecular conformation, shape, and flexibility. *Biomacromolecules*, *8*, 2464–2475.

Patel, T. R., Morris, G. A., Ebringerová, A., Vodenicarová, M., Velebny, V., Ortega, A., et al. (2008). Global conformation analysis of irradiated xyloglucans. *Carbohydrate Polymers*, *74*, 845–851.

Pavlov, G. M., Harding, S. E., & Rowe, A. J. (1999). Normalised scaling relations as a natural classification of linear macromolecules according to size. *Progress in Colloid and Polymer Science*, *113*, 76–80.

Perez, S., Rodríguez-Carvajal, M. A., & Doco, T. (2003). A complex plant cell wall polysaccharide: Rhamnogalacturonan II. A structure in quest of a function. *Biochimie*, *85*, 109–121.

Perrone, P., Hewage, H. C., Thomson, H. R., Bailey, K., Sadler, I. H., & Fry, S. C. (2002). Patterns of methyl and O-acetyl esterification in spinach pectins: A new complexity. *Phytochemistry*, *60*, 67–77.

Pilnik, W., & Voragen, A. G. J. (1970). Pectin substances and their uronides. In A. C. Hulme (Ed.), *The biochemistry of fruits and their products* (pp. 53–87). New York: Academic Press.

Ralet, M.-C., André-Leroux, G., Quéméner, B. C., & Thibault, J.-F. (2005). Sugar beet (*Beta vulgaris*) pectins are covalently cross-linked through diferulic bridges in the cell wall. *Phytochemistry*, *66*, 2800–2814.

Ralet, M.-C., Cabrera, J. C., Bonnin, E., Quéméner, B. C., Hellin, P., & Thibault, J.-F. (2005). Mapping sugar beet pectin acetylation pattern. *Phytochemistry*, *66*, 1832–1843.

Ralet, M.-C., Crépeau, M.-J., & Bonnin, E. (2008). Evidence for a blockwise distribution of acetyl groups onto homogalacturonans from a commercial sugar beet (*Beta vulgaris*) pectin. *Phytochemistry*, *69*, 1903–1909.

Ralet, M.-C., Crépeau, M.-J., Lefebvre, J., Mouille, G., Höfte, H., & Thibault, J.-F. (2008). Reduced number of homogalacturonan domains in pectins of an Arabidopsis mutant enhances the flexibility of the polymer. *Biomacromolecules*, *9*, 1454–1460.

Renard, C. M. G. C., & Jarvis, M. C. (1999a). Acetylation and methylation of homogalacturonans 1; optimisation of the reaction and characterisation of the products. *Carbohydrate Polymers*, *39*, 201–207.

Renard, C. M. G. C., & Jarvis, M. C. (1999b). Acetylation and methylation of homogalacturonans 2; effect on ion-binding properties and conformations. *Carbohydrate Polymers*, *39*, 209–216.

Ridley, B. L., O'Neill, M. A., & Mohnen, D. (2001). Pectins: Structure, biosynthesis and oligogalacturonide-related signaling. *Phytochemistry*, *57*, 929–967.

Rombouts, F. M., & Thibault, J.-F. (1986). Sugar beet pectins: Chemical structure and gelation through oxidative coupling. In M. L. Fishman, & J. J. Jen (Eds.), *The chemistry and function of pectins* (pp. 49–60). Washington, DC: American Chemical Society.

Thibault, J.-F. (1979). Automatisation du dosage des substances pectiques par la méthode au méta-hydroxydiphényle. *Lebensmittel-Wissenschaft und Techologie*, *12*, 247–251.

Thibault, J.-F., Renard, C. M. G. C., Axelos, M. A. V., Roger, P., & Crépeau, M.-J. (1993). Studies of the length of homogalacturonic regions in pectins by acid hydrolysis. *Carbohydrate Research*, *238*, 271–286.

Tollier, M. T., & Robin, J. P. (1979). Adaptation de la méthode à l'orcinol sulfurique au dosage automatique des glucides neutres totaux: conditions d'application aux extraits d'origine végétale. *Annales de Technologie Agricole*, *28*, 1–15.

Tombs, M. P., & Harding, S. E. (1998). *An introduction to polysaccharide biotechnology*. London: Taylor and Francis., pp. 14–20.

Voragen, A. G. J., Pilnik, W., Thibault, J.-F., Axelos, M. A. V., & Renard, C. M. G. C. (1995). Pectins. In A. M. Stephen (Ed.), *Food polysaccharides and their interactions* (pp. 287–340). New York: Marcel Dekker.

Willats, W. G. T., McCartney, L., Mackie, W., & Knox, J. P. (2001). Pectin: Cell biology and prospects for functional analysis. *Plant Molecular Biology*, *47*, 9–27.

Yapo, B. M., Lerouge, P., Thibault, J.-F., & Ralet, M.-C. (2007). Pectins from citrus peel cell walls contain homogalacturonans homogenous with respect to molar mass, rhamnogalacturonan I and rhamnogalacturonan II. *Carbohydrate Polymers*, *69*, 426–435.