Global conformation analysis of irradiated xyloglucans

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A B S T R A C T

Xyloglucan isolated and purified from tamarind seed was subjected to various degrees of γ-irradiation treatments, from 10 to 70 kGy, monitored for radiation damage and then studied using a new combined hydrodynamic approach with regards to conformation and flexibility. Radiation products were analysed with regard to molecular weight (weight average) Mw from size exclusion chromatography coupled to multi-angle laser light scattering (SEC–MALLS), intrinsic viscosity [η] and sedimentation coefficient s20,w. Sedimentation coefficient distributions and elution profiles from SEC–MALLS confirmed the unimodal nature of the molecular weight distribution for each sample in solution. The chain flexibility was then investigated in terms of the persistence length, Lp, of the equivalent worm-like chain model. The traditional Bushin–Bohdanecky (intrinsic viscosity) and Yamakawa–Fujii (sedimentation coefficient) relations were used separately then combined together by minimisation of a target function according to a recently published procedure [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 [see also Ortega, A. Metodologías computacionales para propiedades en disolución de macromoléculas rígidas y flexibles. Ph.D. Dissertation, Universidad de Murcia, 2005]] and yielded an estimate for Lp in the range 4–9 nm using floated and fixed mass per unit length analysis protocols and “point” global analysis: irradiated xyloglucans behave as flexible structures in common with pressure/heat treated materials.

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1. Introduction

Xyloglucan (XG) from the seed kernels of Tamarindus indica L. is a plant cell wall polysaccharide consisting of a β (1→4)-D-glucan backbone, which is partially substituted at position 6 of the glucopyranosyl units mainly by single α-D-xylopyranosyl residues as well as by disaccharide side chains composed of β-D-galactopyranosyl-(1→2)-α-D-xylopyranosyl residues (Gidley et al., 1991; Nishinari, Yamatoya, & Shirakawa, 2000). Its repeating unit belongs to the XXXG type, consisting of three consecutive xylosylated glucopyranose units (X) separated by at least one unsubstituted glucopyranose unit (G), whereby some of the xylose units bear a galactopyranose unit (L) (Fig. 1). Recently, the structural motifs of the tamarind seed xyloglucan existing mainly as heptasaccharide (GlcαXylβ, motif XXXG), octasaccharide (GlcαXylβGal, motif XXLG), and monosaccharide (GlcαXylβGal2, motif XLLG) have been reported (Hoffman et al., 2005).

The use of water soluble xyloglucan isolated from the endosperms of seeds of T. indica, is expanding from textile and food to pharmaceutical and cosmetic industries. This expansion of interest is due to its particular physicochemical properties and spectrum of biological activities (Burgalassi et al., 2000; Shankaracharya, 1998; Sreelekha, Vijayakumar, Ankanthil, Vijayan, & Nair, 1993). Many of the functional properties of xyloglucan, in common with other polysaccharides, depend on molecular weight. Production of polysaccharides of lower molecular weight by whatever means is of particular interest to the biomedical and healthcare industries, as lower molecular material offers the advantage of improved diffusion into biological tissues: the use of irradiative methods for producing lower molecular weight material is one such method and is explored here.

Several reports on the solution properties of xyloglucan from tamarind seed and Detarium senegalense have already been published (Lang & Burchard, 1993; Lang & Kajiwara, 1993; Picout, Ross-Murphy, Errington, & Harding, 2003; Wang, Ellis, Ross-Murphy, & Burchard, 1997). The most recent work (Picout et al., 2003) has focussed on the need to provide adequate solubilisation
particularly with regard to the higher molecular weight material using appropriate assisted dispersal methods involving pressure and temperature. In this present study we are not able to follow this advised procedure primarily as it would obscure the effects of irradiation damage, which we are trying to assess. However since, with the exception of the un-irradiated sample, we are dealing with lower molecular weight xyloglucans the presence of incompletely dispersed material (which will be removed by ultracentrifugation anyway) will not be as serious a problem because of their higher solubility. We still thought have to take particular care to ultracentrifuge all samples prior to analysis (and final concentration assignment).

Besides pressure and temperature treatment (Picout et al., 2003), other methods for depolymerisation/degradation of xyloglucans have involved oxidative scission by hydroxyl radicals (Fry, 1999; Schweiker, Liszakay, & Schopfer, 2000) and the generation of oligosaccharides by enzymatic treatment (Strickland et al., 1999). However neither oxidative scission nor enzymatic treatments are aimed at preserving the structural features of the parent polymer. The application of irradiation treatment to xyloglucan in this study is designed to break the main chains without changing the structural features: there should be no substantial change in sugar composition of the heteropolysaccharides, the only major effect being a reduction in the size of the polysaccharide with increase in radiation treatment. In this regard a recently published study (Vodenicarova, Drimalova, Hromadkova, Malovikova, & Ebringerova, 2006) probed the effect of various radiation treatments on the chemical and structural properties and molecular weight of tamarind seed xyloglucan. It was shown by those researchers that depolymerisation by γ-irradiation at doses up to 50 kGy resulted in no significant change in the degree of branching of the residual polymer chains, with a suggestion of a small increase >50 kGy. The present study now focuses on the hydrodynamic properties of a series of tamarind seed xyloglucan fractions prepared by γ-irradiation according to Vodenicarova et al. (2006) to assess the molecular flexibility of these molecules, and to take advantage of some recent advances in data analysis and to see if there is any significant change in flexibility at high irradiation doses.

### 2. Materials

The xyloglucan sample XG-0, produced by CPN, spol. s r.o. (Dolní Dobrouč, Czech Republic), was irradiated in dry air at room temperature using a 60Co source (Perun, Artim s r.o., Prague, Czech Republic). The irradiation doses ranged from between 10 and 70 kGy yielding samples XG-10 (10 kGy), XG-20 (20 kGy), XG-30 (30 kGy), XG-40 (40 kGy), XG-50 (50 kGy) and XG-70 (70 kGy). Their monosaccharide compositions are shown in Table 1.

### 3. Methods

#### 3.1 Sedimentation velocity

Sedimentation coefficients were evaluated using the Beckman Optima XL-I analytical ultracentrifuge (Beckman Instruments, Palo Alto, USA). Solvent (400 μL) and sample (380 μL) were injected into the solvent and sample channels of the 12 mm, double sectored carbon filled centrepiece. Cells were then loaded into an 8-hole titanium rotor and placed in the centrifuge. Samples were run at 40,000 rpm and 20.0 °C throughout. Concentration profiles of the ultracentrifuge cells were registered using the Rayleigh interference optical system (Ralston, 1993).

Solute concentration distributions recorded over the time-course of the sedimentation experiment (scans every 4 min) were analysed using the finite-difference algorithm SEDFIT (Schuck & Rossmanith, 2000) in terms of an apparent distribution of sedimentation coefficients in the form of $g(s)$ versus $s_{20,\text{w},\text{g}}$ where the $g$ indicates that the distribution of sedimentation coefficients has not been corrected for diffusion effects. Scans were used from attainment of meniscus depletion up to the point at which the mid-point of the boundary had traversed a further ~20% of column length which meant that ~40 scans were analysed (regularisation was set to 0.68). The sedimentation coefficient, $s$ for each concentration (from the mode of the main peak position of the $g(s)$ distribution) was then corrected to standard solvent conditions (density and viscosity of water at 20 °C) to yield $s_{20,\text{w}}$ (Schachman, 1959). To eliminate the effect of non-ideality, $s_{20,\text{w}}$ was further extrapolated to zero concentration to obtain $s_{20,\text{w}}^*$ (for asymmetric molecules in non-ideal systems (Harding, 1995, 1997) reciprocal (1/$s_{20,\text{w}}^*$) versus concentration plots generally give more reliable estimates for $s_{20,\text{w}}^*$ (Table 2).

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Radiation (kGy)</th>
<th>Glc: Xyl: Gal (mole ratios)</th>
<th>Xyl: Gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>XG-0</td>
<td>0</td>
<td>1:0.68:0.32</td>
<td>2:1:1</td>
</tr>
<tr>
<td>XG-10</td>
<td>10</td>
<td>1:0.64:0.31</td>
<td>2:1:1</td>
</tr>
<tr>
<td>XG-20</td>
<td>20</td>
<td>1:0.63:0.31</td>
<td>2:0:1</td>
</tr>
<tr>
<td>XG-30</td>
<td>30</td>
<td>1:0.66:0.31</td>
<td>2:1:1</td>
</tr>
<tr>
<td>XG-40</td>
<td>40</td>
<td>1:0.64:0.32</td>
<td>2:1:1</td>
</tr>
<tr>
<td>XG-50</td>
<td>50</td>
<td>1:0.60:0.32</td>
<td>1:9:1</td>
</tr>
<tr>
<td>XG-70</td>
<td>70</td>
<td>1:0.78:0.36</td>
<td>2:2:1</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>$s_{20,\text{w}}$ (S)</th>
<th>[n] (mL/g)</th>
<th>$10^{-1} \times M_w$ (g/mol)</th>
<th>$M_w/M_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>XG-0</td>
<td>7.21 ± 0.03</td>
<td>405 ± 35</td>
<td>70.0 ± 5.0</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>XG-10</td>
<td>4.66 ± 0.03</td>
<td>210 ± 10</td>
<td>27.0 ± 1.0</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>XG-20</td>
<td>3.10 ± 0.04</td>
<td>170 ± 10</td>
<td>15.8 ± 0.3</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>XG-30</td>
<td>3.30 ± 0.01</td>
<td>140 ± 10</td>
<td>12.7 ± 1.0</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>XG-40</td>
<td>2.82 ± 0.04</td>
<td>135 ± 5</td>
<td>9.7 ± 1.0</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>XG-50</td>
<td>2.80 ± 0.08</td>
<td>100 ± 5</td>
<td>6.0 ± 0.4</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>XG-70</td>
<td>2.61 ± 0.02</td>
<td>75 ± 5</td>
<td>4.5 ± 0.3</td>
<td>1.1 ± 0.1</td>
</tr>
</tbody>
</table>

### Figure 1

![Structural features of tamarind seed xyloglucan. R:H (motif XXXG) or β-α-galactopyranose (motif XXLG).](image-url)
3.2. Viscometry

The intrinsic viscosity of each xyloglucan sample was measured using a semi-automated viscosity measuring unit (AVS 310, Schott Geräte, Hofheim, Germany) at a temperature of (20.00 ± 0.01 °C) in an Ostwald viscometer. Relative dynamic viscosities $\eta_{rel}$ were calculated using (Huggins, 1942).

$$\eta_{rel} = \left( \frac{t}{t_0} \right) \left( \frac{\rho}{\rho_0} \right) = \frac{t}{t_0}$$

(1)

where $t$ and $\rho$ refer to the flow time and density for xyloglucans respectively, and $t_0$ and $\rho_0$ are solvent flow time and density, respectively. Since concentrations were low (<2 $\times 10^{-3}$ g mL$^{-1}$) the density correction term was considered negligible. Reduced specific viscosities $\eta_{red}$ (mL g$^{-1}$) were then determined across a range of concentration $c$ (between 0.1 and 2 $\times 10^{-3}$ g mL$^{-1}$):

$$\eta_{red} = (\eta_{rel} - 1)/c$$

(2)

and intrinsic viscosities [$\eta$] were calculated from extrapolation of $\eta_{red}$ to zero concentration (Huggins, 1942) to eliminate non-ideality.

3.3. Size exclusion chromatography coupled to multi-angle laser light scattering (SEC–MALLs)

Molecular weights (weight averages, number averages and distributions) were estimated using SEC–MALLs (Wyatt, 1992). The SEC system used consisted of a Jasco HPLC pump (Model PU-1580, Jasco Corporation, Tokyo, Japan), a Phenomenex guard column (Phenomenex, Macclesfield, UK), and TSK (Tosoh Biosciences, Tokyo, Japan) Gel G4000 PW and Gel G3000 PW columns connected in series. An on-line de-gasser was used to remove gas from the eluent. A flow rate of 0.8 mL min$^{-1}$ was used. The mobile phase was the phosphate buffered saline at pH 7.0, the size exclusion system after initially centrifuging at 40,000 rpm for 15 min (Beckman L8-55 M Ultracentrifuge, Beckman Instruments, Palo Alto, USA) and filtering through 0.45 μm filters (Whatman, Maidstone, England). It is also possible to estimate (z-average) radii of gyration $R_g$ for particles large enough so there is a measurable dependence of the scattering function $K/R_0$ on scattering angle $\theta$, where $R_0$ is the Rayleigh excess ratio (a measure of the difference in intensity between the scattered light and incident light), $c$ is the concentration (g/mL) and $K$ is a scattering ‘constant’ depending on the wavelength, refractive increment $dn/dc$ (ml/g) and refractive index of the medium $n_o$. However in this study only for the unfractionated sample was there a significant angular dependence allowing $R_g$ to be estimated (Patel, Picout, Ross-Murphy, & Harding, 2006).

4. Results and discussion

4.1. Sample purity: sedimentation coefficient and molecular weight distributions

Sedimentation coefficient distributions were registered for the untreated (XG-0) and irradiated (XG-10–XG-70) samples at all the concentrations studied. In every case the samples showed a strong degree of unimodality (Fig. 2) but with some evidence of the existence of discrete (i.e. non-continuous) heterogeneity at higher molecular weights.

The $g(s)$ distribution for each of these plots reflect the effect of $\gamma$-radiation on the macromolecular chain. The sedimentation coefficient, a very sensitive parameter to molecular weight, is seen to decrease steadily with increase in severity of radiation treatment (see Table 2) indicating a progressive scission of the polysaccharide chains. Additionally, it was also observed that there was an increase in the width of the main peak with increasing treatment. This is consistent with an increase in polydispersity, although quantitative estimates are difficult because contributions to the broadening could also arise from increased diffusion and decreased hyper-sharpening though decreased size and hence non-ideality (Dhami et al., 1995; Morris et al., 2001). Molecular weight distribution analysis from SEC–MALLs confirms these observations (Fig. 3), and quantitative estimates for the polydispersity (from the ratio of the weight average $M_w$ to the number average $M_n$) are consistent with the treated samples being more polydisperse than the native material.

![Fig. 2. $g(s)$ distributions for xyloglucans: XG-0 at a loading concentration $c = 1.0$ mg/mL (■). The main peak $s$ value = 4.38 S, XG-20 at 1.0 mg/mL (▲), $s = 2.91$ S, XG-50 at 1.2 mg/mL (●), $s = 2.71$ S, XG-70 at 1.2 mg/mL (★), $s = 2.31$ S.](image)

![Fig. 3. Molecular weight distributions for xyloglucans: XG-0 (■), XG-10 (●), XG-20 (▲), XG-30 (●) and XG-40 (★).](image)
4.2. Intrinsic viscosity

The intrinsic viscosity was measured by extrapolation of the reduced viscosity $\eta_{\text{red}}$ to zero concentration (Huggins, 1942) and was seen to decrease with increase in $\gamma$-radiation treatment (Table 2).

4.3. SEC–MALLs and weight average molecular weights

Elution profiles for the untreated and irradiated xyloglucans were largely unimodal, consistent with the sedimentation velocity data. Values for the weight average molecular weight ($M_w$) for all samples measured using SEC–MALLs are presented in Table 2, showing a steady decrease with increasing treatment. The polydispersity ratio $M_w/M_n$ also increases after mild irradiation and remains essentially constant thereafter. A radius of gyration of ($76 \pm 2$ nm) was estimated for the untreated sample and "$<50$ nm" for the other samples.

4.4. Conformational analysis

Hydrodynamic results obtained from SEC–MALLs, sedimentation velocity and viscosity measurement were further used to study the gross conformation of xyloglucans (Harding, Vårum, Stokke & Smidsrød, 1991), taking advantage of the fact that the radiation at various levels yielded different values for weight average molecular weight, $M_w$, facilitating the use of the “Mark–Houwink–Kuhn–Sakurada”- (MHKS)-type power law relations linking $[\eta]$ and $s_{20w}$ with $M_w$:

$$[\eta] \propto M_w^a$$

$$s_{20w} \propto M_w^b$$

The MHKS exponent ($a$), and sedimentation exponent ($b$) are derived using double logarithmic plots of respectively, intrinsic viscosities and sedimentation coefficients versus molecular weights (Fig. 4), and the values obtained are reported in Table 3. This procedure assumes a homologous series for the polymers (i.e. they all have approximately the same conformation type): any departure would reveal itself as non-linearity of the logarithmic plots.

The values estimated for both parameters are suggestive of a flexible coil molecule. The exponents are within the typical range for flexible chains with dominant hydrodynamic interaction in good solvents. These values only refer however to the average for flexible coil molecules. The exponents are within the typical range for flexible chains with dominant hydrodynamic interaction in good solvents. These values only refer however to the average for flexible coil molecules.

4.5. Estimation of persistence length

4.5.1. The Bushin–Bohdanecky method (Bohdanecky, 1983; Bushin, Tsvetkov, Lysenko & Emelyanov, 1981)

This is one of the most popular methods for estimating chain persistence lengths particularly for semi-flexible polymers, and has been applied to range of polysaccharides from charged polysaccharides including xanthan (Sato, Norisuye, & Fujita, 1984), sodium hyaluronate (Mendichi, Soltes, & Schierone, 2003) as well as galactomannans (Gomez, Navarro, Manzanares, Horta, & Car-
4.5.2. The Yamakawa–Fujii method

Hearst and Stockmayer (1962) first reported the sedimentation coefficient in relation to worm-like chain parameters, later refined by Yamakawa and Fujii (1973). The original relation given by Yamakawa and Fujii (1973) showed that A2 = −ln(d/2Lp) and A3 = 0.1382 if the Lp is much higher than the chain diameter, d. Using the Yamakawa–Fujii procedure a plot of s2,20,w versus Mw,1/2 (Fig. 6) yielded a slope of (7.6 ± 0.7) × 10^{-3}, and from Eq. (7) and a fixed Mw of 537 g mol^{-1} again the Lp = (8 ± 1) nm somewhat higher than from the Bushin–Bohdanecky analysis but still well within the flexible coil range.

\[ s^2 = \frac{M_0(1 - \bar{v}_p)}{3\pi\eta_0N_A} \times \left[ 1.843 \left( \frac{M_w}{2M_pL_p} \right)^{1/2} + A_2 + A_3 \left( \frac{M_w}{2M_pL_p} \right)^{-1/2} + \ldots \right] \]

Yamakawa and Fujii (1973) showed that A2 = −ln(d/2Lp) and A3 = 0.1382 if the Lp is much higher than the chain diameter, d. Using the Yamakawa–Fujii procedure a plot of s2,20,w versus Mw,1/2 (Fig. 6) yielded a slope of (7.6 ± 0.7) × 10^{-3}, and from Eq. (7) and a fixed Mw of 537 g mol^{-1} again the Lp = (8 ± 1) nm somewhat higher than from the Bushin–Bohdanecky analysis but still well within the flexible coil range.

4.5.3. Combined analysis

Different methods provide their own bias on results (Bohdanecky & Petrus, 1991; Picout, Ross-Murphy, Jumel, & Harding, 2002) and in response to this problem Ortega and García de la Torre have created a new software package, Multi-HYDFIT (Ortega & García de la Torre, 2007) which considers data sets of both intrinsic viscosities for different molecular weights and sedimentation coefficients for different molecular weights. It then performs a minimisation procedure finding the best values of Mw and Lp and chain diameter d satisfying the Bushin–Bohdanecky (Bohdanecky, 1983; Bushin et al., 1981) and Yamakawa–Fujii (Yamakawa & Fujii, 1973) equations. Extensive simulations have shown that values returned for Mw and Lp are insensitive to d so this is usually fixed (Ortega & García de la Torre, 2007).

For the xyloglucans we considered two possible cases:

1. Chain diameter, d was fixed at 0.9 nm and the mass per unit length, Mw, was fixed at 537 g mol^{-1} nm^{-1} (we considered each xyloglucan separately and as a pseudo-homologous series). A value of d = 0.9 nm can be calculated from the partial specific volume and mass per unit length using Eq. 23 of Bohdanecky (1983). The value for Mw is obtained from the ratio of the average molar mass of the structural unit (290) to its length (0.54 nm).

2. Only the chain diameter, d was fixed at 0.9 nm. The Multi-HYDFIT program then "floats" the variable parameters (Lp in case 1, Lp and Mw in case 2) in order to find a minimum of the multi-sample target (error) function (Ortega & García de la Torre, 2007), \( \Delta \).

In this procedure as defined in Ortega and García de la Torre (2007), \( \Delta \) is calculated using equivalent radii (or the ratio of equivalent radii), where an equivalent radius is defined as the radius of an equivalent sphere having the same volume as the determined property. These 'determined properties' include the translational frictional coefficient, f (calculated from either the diffusion or sedimentation coefficients), intrinsic viscosity, \( [\eta] \), radius of gyration, \( R_g \), or the rotational relaxation time, \( \tau \). In the present study we are interested in the equivalent radii resulting from the sedimentation coefficient i.e. translational frictional coefficient (aT) and from the intrinsic viscosity (aI).

\[ a_T = \frac{f}{6\pi\eta_0} \]

where \( \eta_0 \) is the viscosity of water at 20.0 °C, and

\[ a_I = \left( \frac{3[\eta]M_w}{10\pi N_A} \right)^{1/3} \]

where \( N_A \) is Avogadro’s number.

The target function, \( \Delta \) can be evaluated from this relation:

\[ \Delta^2 = \frac{1}{N_i} \sum_{i=1}^{N_i} \left( \sum W_i \right)^{-1} \sum W_i \left( \frac{a_{i(s)} - a_{i(exp)}}{a_{i(exp)}} \right)^2 \]

and this one

\[ \Delta^2 = \frac{1}{N_i} \sum_{i=1}^{N_i} \left( \sum W_i \right)^{-1} \sum W_i \left( \frac{a_{i(cal)} - a_{i(exp)}}{a_{i(exp)}} \right)^2 \]

where \( N_i \) is the number of samples in multi-sample analysis, \( W_i \) and \( W_i \) are the statistical weights for equivalent radii \( aT \) and \( aI \) (from translation frictional coefficient and intrinsic viscosity data, respectively) and the subscripts cal and exp represent values from calculated and experimental values, respectively. \( \Delta \) is thus a dimensionless estimate of the agreement between the theoretical
In the first case (Fig. 7) where both the diameter and the mass per unit length are fixed we estimate a persistence length of \( \Delta L = 6 \pm 1 \text{ nm} \) for a particular persistence length, calculated values for the translational frictional coefficient (consequently the sedimentation coefficient) and the intrinsic viscosity for a particular persistence length, \( L_p \) (and mass per unit length, \( M_1 \) in case 2) and the experimentally measured parameters (Ortega & García de la Torre, 2007).

In the second case (Fig. 8) where the depression (blue end of the colour spectrum) in the contour plot (where \( \Delta \) varies by less than the error in the experimental data) gives the same answer within experimental error, namely \( L_p = 6 \pm 1 \text{ nm} \) and \( M_1 = 510 \pm 60 \text{ g mol}^{-1} \text{ nm}^{-1} \).

Furthermore using “point” global determinations, that is to say we use \( [\eta] \), \( s_{20,w} \) and \( M \) values for each irradiation does to estimate \( L_p/M_1 \), (and hence \( L_p \) for an \( M_1 = 510 \pm 60 \text{ g mol}^{-1} \text{ nm}^{-1} \) for each dose) there is within the error margin no significant difference in persistence lengths between the samples. This is consistent with the sugar composition data (Table 1) which shows that the Glc:Xyl ratios of xyloglucan before and after \( \gamma \)-irradiation (<50 kGy) showed no significant differences as they varied from 1:0.68 to 1:0.60, and the Xyl:Gal ratios varied from 2.1–1.9:1. At 70 kGy, the Glc:Xyl ratio increased to 1:0.78, but the Xyl:Gal ratios remained unchanged. The combined results indicate that the overall flexibility of the molecule is not markedly changed, i.e. the series of polymers is pseudo-homologous as far as hydrodynamic properties are concerned (Table 4).

The values for each irradiated xyloglucan. Corresponding persistence lengths also given for \( M_1 = 537 \text{ g mol}^{-1} \text{ nm}^{-1} \).

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