

Research paper

Correlation of T_2 NMR with T_g/T and viscosity

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ABSTRACT

Using both literature and new experimental data, we demonstrate that T_2 relaxation times are governed by the ratio T_g/T , where T_g is the moisture-dependent glass transition temperature and T is the actual temperature. This ratio, T_g/T , is known to control the viscosity and plasticizing behavior of small carbohydrates, as well as the rheological properties of biopolymeric systems such as starch and plant proteins. For small carbohydrates, the T_2 data collapse onto a universal master curve, analogous to their viscosity behavior. For biopolymers, however, the current dataset is insufficient to confirm the existence of such a master curve. Additionally, we show that T_2 NMR provides an accurate estimate of the glass transition temperature of small carbohydrates, with deviations within 1%–2%. This makes it a promising method for high-throughput screening of the plasticizing properties of novel sugar replacers.

1. Introduction

In their study on sugar replacement in cake, Godefroidt et al. (2023) reported a correlation between T_2 relaxation times (as measured by NMR) and the (intermolecular) hydrogen bond density, $n_{OH,eff}$. The latter parameter is central to our sugar replacement strategy (van der Sman et al., 2022), where we have shown that $n_{OH,eff}$ governs the texture and rheology of bakery products.

Previously, we demonstrated that $n_{OH,eff}$ also controls both the viscosity (Van der Sman and Mauer, 2019) and the glass transition temperature T_g (Van Der Sman, 2013) of carbohydrate solutions. Consequently, the ratio T_g/T —the glass transition temperature over the actual temperature—emerges as a key parameter controlling the viscosity of these systems (Van der Sman and Mauer, 2019; Van der Sman and Meinders, 2013; Longinotti and Corti, 2008). Mora-Gutierrez and Baianu (1989) also proposed that T_2 relaxation times are linked to intermolecular hydrogen bonding, akin to our $n_{OH,eff}$ parameter. Similarly, Asghari et al. (2025) suggested that T_2 relaxation times reflect hydrogen bond strength in carbohydrate solutions.

Aschenbrenner et al. (2014) correlated T_2 relaxation times with the temperature difference $T - T_g$, observing that data for lactose solutions collapse onto a single curve, though this was not the case for trehalose

or dextran. More broadly, we have found that the temperature ratio T_g/T governs the rheological behavior of various food biopolymer systems, including starch, maltodextrins, and plant proteins (Van der Sman et al., 2022; Siemons et al., 2022; van der Sman et al., 2023, 2024; Purcell et al., 2025).

Traditionally, the glass transition temperature of food systems is measured using differential scanning calorimetry (DSC) (Renzetti et al., 2021) or dynamic mechanical analysis (DMA) (Veser et al., 2024). However, in complex systems involving biopolymers and co-plasticizers such as sugars, DSC often fails to provide a clear glass transition signal (Masavang et al., 2019). DMA also has limitations in determining T_g due to the broad nature of the transition in such systems (Cuq et al., 1997; Hundal and Takhar, 2009; Mendieta-Taboada et al., 2008).

This raises two key questions: (a) can T_2 relaxation times obtained from low-field NMR serve as an alternative method for determining the T_g/T parameter? and (b) do T_2 relaxation times correlate with the viscosity of food materials where hydrogen bonding dominates molecular interactions?¹

Independent studies support this link between T_2 relaxation and rheology. For example, correlations have been observed in protein-rich 3D-printing inks (Chen et al., 2021; Phuhongsung et al., 2020),

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¹ Note, that the same symbol T is used for temperature and relaxation time, in agreement with common practice in physics and NMR literature. To avoid any ambiguity, the relaxation times will always be denoted with subscripts, like T_1 and T_2 , and temperature is denoted without subscripts, and often in the combination T_g/T .

carbohydrate solutions (Sato and Miyawaki, 2007), and microcrystalline cellulose suspensions (Ono et al., 1998). Sacchetti et al. (2014) also reported a correlation between T_2 and viscosity in carbohydrate solutions. Ruan et al. (1999) used both T_1 and T_2 NMR to determine the glass transition of maltodextrins. In the glassy state T_2 take a constant value, while T_1 depends on temperature and moisture content, while in the rubbery state they show the reverse behavior, i.e. a constant T_1 value and a varying T_2 value. The transitions in T_1 and T_2 are used to determine T_g . Deng et al. (2014) noted that both T_1 and T_2 correlate with viscosity, and that 2D NMR measurements combining T_1 and T_2 may offer additional insights.

This relationship between NMR relaxation times and viscosity is a foundational aspect of the theory developed by Bloembergen et al. (1948). Nuclear spin relaxation arises from time-dependent local magnetic field fluctuations, which are generated by molecular rotational and translational motion—modulating dipole–dipole interactions between nuclear spins. In the theory the relaxation times relate to rotational diffusion. For (nearly) spherical molecules this can be linked to viscosity, via the Stokes–Einstein theory.

Given our theoretical framework, in which the viscosity of carbohydrate solutions scales with the temperature ratio T_g/T , we hypothesize that T_2 relaxation times should similarly scale with T_g/T .

As the glass transition behavior of carbohydrates such as sugars is well established (Van der Sman and Mauer, 2019), we have focused our investigation on these systems to test our hypothesis. Specifically, we utilize (1) literature data on T_2 relaxation times of carbohydrates and pure water, and (2) new experimental data obtained on carbohydrate solutions and biopolymeric samples (soy and maize flour). We examine the correlation between the temperature ratio T_g/T and both the T_2 relaxation time and the viscosity of the carbohydrate solutions.

2. Materials and methods

2.1. NMR relaxation measurements

The literature data were obtained using benchtop low-field NMR analyzers, employing either Free Induction Decay (FID) or Carr–Purcell–Meiboom–Gill (CPMG) pulse sequences (van den Dries et al., 1998; Mora-Gutierrez and Baianu, 1989; Asghari et al., 2024; Sultana et al., 2024). Continuous T_2 relaxation time spectra were derived using the standard inverse Laplace transform method (CONTIN). In our analysis, we considered only the T_2 relaxation time corresponding to the main peak (i.e., the signal with the largest amplitude).

For our own NMR measurements, we used a 20 MHz minispec mq 20 benchtop NMR spectrometer (Bruker, Germany). Carbohydrate samples were analyzed using a CPMG pulse sequence with an echo time of 0.2 ms and a train of 32,000 echoes. The number of scans was set to 4, with a recycle delay of 30 s. Background correction was performed using measurements from an empty sample tube. Each CPMG dataset was reduced to 2000 geometrically spaced data points before fitting the decay curves using CONTIN.

For biopolymer samples, a combined FID-CPMG sequence was used. The FID acquisition time was 0.1 ms, followed by a CPMG pulse train with an echo time of 0.2 ms and 1000 data points. The number of scans was set to 8, with a recycle delay of 8 s. Each sample was measured in triplicate. Measurements were conducted after incubation at 20, 40, and 60 °C for 30 min, respectively.

Differences between datasets may arise due to variations in magnetic field strength (B), or equivalently, angular frequency (ω), which are linearly related via the Larmor resonance frequency:

$$\omega = \gamma_H B,$$

where $\gamma_H = 2.675 \times 10^8$ rad/s/T for ^1H protons. A 20 MHz spectrometer typically corresponds to a magnetic field strength of approximately 0.5 T.

Table 1

Data sources used for the correlation of T_2 with T_g/T .

Compound	Reference
Glucose, fructose, sucrose	Mora-Gutierrez and Baianu (1989)
water	Vesanen et al. (2013)
Fructose, Glucose, Galactose	Asghari et al. (2024)
Lactose, Maltose, Sucrose	Sultana et al. (2024)
Maltose	van den Dries et al. (1998)
maltodextrin DE42	Kumagai and Kumagai (2002)
Maltose	Hills and Pardoe (1995)

The Bloembergen–Purcell–Pound (BPP) relation (Bloembergen et al., 1948) describes the dependence of T_2 on molecular motion:

$$\frac{1}{T_2} = C \left[a\tau_c + b \frac{\tau_c}{1 + (\omega\tau_c)^2} \right],$$

where τ_c is the correlation time of molecular motion. At low magnetic fields, where $\omega\tau_c \ll 1$, the relation simplifies to $1/T_2 \sim \tau_c$. Since τ_c is expected to follow the same temperature and moisture dependence as viscosity (Zielinski et al., 1992), a logarithmic relationship between T_2 and T_g/T is anticipated, i.e., $\log(T_2) \sim T_g/T$, similar to the relations between T_g/T and rheological properties of carbohydrate solutions, polysaccharides and proteins (Van der Sman and Mauer, 2019; van der Sman et al., 2023; Van der Sman et al., 2022).

2.2. Computation of glass transition

The glass transition temperature T_g of carbohydrate solutions is calculated using the Couchman–Karasz equation:

$$T_g = \frac{y_w T_{g,w} \Delta C_{p,w} + y_s T_{g,s} \Delta C_{p,s}}{y_w \Delta C_{p,w} + y_s \Delta C_{p,s}} \quad (1)$$

where $y_w = 1 - y_s$ is the mass fraction of water, $T_{g,w} = 139$ K is the glass transition temperature of pure water, and $T_{g,s}$ is the glass transition temperature of the dry solute. Mass fractions are readily calculated from the set concentrations of the investigated carbohydrate solutions.

The specific heat capacity changes during the glass transition are $\Delta C_{p,w} = 1.92$ kJ/kg for water, $\Delta C_{p,s} = 0.425$ kJ/kg for sugars, and $\Delta C_{p,s} = 0.85$ kJ/kg for polyols and amino-acids (Van Der Sman, 2013; Van der Sman et al., 2020). The latter value has been found to be universal for carbohydrates with molar masses $M_w \geq 180$ g/mol (Van Der Sman, 2013). Values for $T_{g,s}$ of various carbohydrates are tabulated in Van der Sman and Mauer (2019).

3. Results

3.1. T_2 relaxation times of carbohydrates

We first collected T_2 relaxation time data for carbohydrate systems and pure water from the literature, as summarized in Table 1. Several sources (Hills and Pardoe, 1995; van den Dries et al., 1998; Kumagai and Kumagai, 2002) are of particular interest, as they report data for systems near or within the glassy state, i.e. $T_g/T > 1$. The remaining datasets pertain to carbohydrate solutions in the rubbery or liquid-like state, i.e. $T_g/T < 1$.

All collected data were correlated with the estimated T_g/T ratio, where T is the temperature at which the NMR measurement was performed, and T_g is the moisture-dependent glass transition temperature of the carbohydrate solution. The glass transition temperature T_g was computed using the Couchman–Karasz relation (Eq. (1)), employing tabulated values of the dry solute glass transition temperature $T_{g,s}$ from our previous work (Van der Sman and Mauer, 2019). These $T_{g,s}$ values are primarily based on DSC measurements.

Fig. 1 presents the literature T_2 data as a function of the estimated T_g/T . The results are highly promising: $\log(T_2)$ exhibits a linear relationship with T_g/T in the range $T_g/T < 1$. For $T_g/T > 1.05$, the

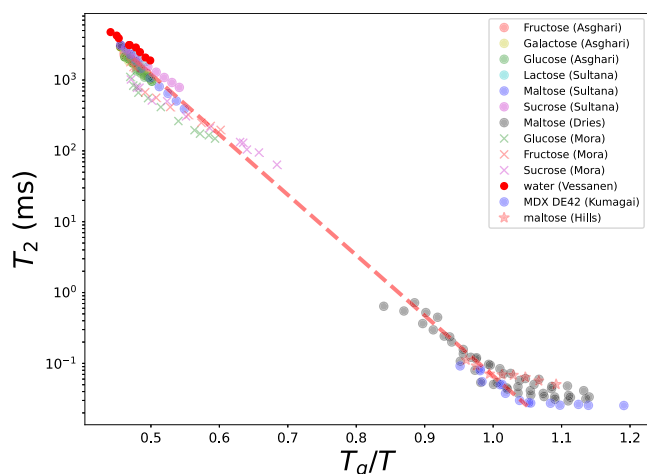


Fig. 1. T_2 relaxation time of various carbohydrate solutions and glasses, with data collected from literature as listed in Table 1. The dashed line indicates the fitted trend line connecting the values of pure water at room temperature, and the universal mobility state of carbohydrate systems in the glassy state (with $T_g/T = 1.05$).

relaxation time plateaus at a universal value of approximately 0.02 ms. This limiting value is consistent with findings by Kalichevsky et al. (1993) and Aschenbrenner et al. (2014).

The observed plateau can be interpreted through the isoviscosity assumption of the glassy state (Angell, 2002), which posits a universal viscosity $\eta = \eta_g \approx 10^{13}$ Pa.s. Notably, the leveling off of T_2 values does not occur precisely at $T_g/T = 1$, but rather at $T_g/T = 1.05$. This aligns with previous observations that the T_g determined via T_2 NMR is approximately 30 °C higher than that obtained from DSC (Kalichevsky et al., 1992, 1993; Yoshioka et al., 1999).

Based on the universality of the T_2 value in the glassy state and the well-established T_2 value of pure water, we have included a trend line in Fig. 1. This trend-line was obtained via linear regression between T_g/T and $\log(T_2)$ in the range $T_g/T < 1.0$. This rendered a strong correlation of $r^2 = 0.996$. Extrapolation of the trend line to the plateau value of $T_2 = 0.02$ ms, confirms the limiting value of $T_g/T = 1.05$. Despite this high correlation, we note a significant gap in the collected dataset in the range $0.7 < T_g/T < 0.9$. The occurrence of this gap is probably explained by the solubility limitations of plasticizers in aqueous solutions, which are limited to the range $0.4 < T_g/T < 0.7$. In the range $T_g/T > 0.9$ shelf-stable powders at low water activities are used. Still, we encourage researchers to produce data to fill this gap.

This trend line can be used for comparison with new experimental data, or to establish their glass transition temperature $T_{g,s}$. As an exercise, we estimate those for glucose and fructose in the next section.

3.2. Glass transition of glucose and fructose

In our earlier study (Van der Sman and Mauer, 2019), we assumed that the dry glass transition temperatures ($T_{g,s}$) of fructose and glucose are similar. However, several studies suggest that this may not be the case (Arvanitoyannis et al., 1993; Cruz et al., 2001; Saavedra-Leos et al., 2012; Schugmann and Foerst, 2022). Table 4 lists various reported values of $T_{g,s}$ for fructose and glucose from the literature. To evaluate the accuracy of T_2 -NMR in determining $T_{g,s}$, we analyzed the T_2 relaxation data from Asghari et al. (2024) for both sugars. We note, that these measurements are done at constant temperature ($T = 32$ °C).

If fructose and glucose indeed have similar $T_{g,s}$ values, their viscosity data should overlap. To test this, we compiled viscosity data from the literature (Table 2). We observe that for $T_g/T < 0.6$, the viscosity data of fructose and glucose are nearly identical. However, near the

Table 2
Viscosity data sources.

Compound	Reference
Fructose	Ollett and Parker (1990)
Fructose	Telis et al. (2007)
Glucose	Ollett and Parker (1990)
Glucose	Telis et al. (2007)
Sucrose	Telis et al. (2007)
Sucrose	Swindells et al. (1958)
Sucrose	Longinotti and Corti (2008)
Trehalose	Longinotti and Corti (2008)

Table 3
Carbohydrates used in new T_2 measurements.

Compound	$T_{g,s}$ (K)	Reference	RSME
Erythritol	225	Van der Sman and Mauer (2019)	0.046
Mannitol	266	Van der Sman and Mauer (2019)	0.065
Arabinose	274	Van der Sman and Mauer (2019)	0.077
Allulose	274	Allan and Mauer (2022)	0.067
Fructose	286	this paper	0.048
Sucrose	336	Van der Sman and Mauer (2019)	0.087
Lactose	354	Van der Sman and Mauer (2019)	0.105
Trehalose	388	Van der Sman and Mauer (2019)	0.118
Promitor	425	Woodbury and Mauer (2022)	0.262
Nutriose	422	Renzetti et al. (2025)	0.094
Cellobiose	375	Thorat et al. (2018)	0.098
Proline	250	Van der Sman et al. (2020)	0.021
FOS IQ	372	Renzetti et al. (2025)	0.116
Polydextrose (PDX)	353	Renzetti et al. (2025)	0.097
XOS	375	Renzetti et al. (2026)	0.138
FOS Actilight	315	Renzetti et al. (2025)	0.089
FOS OFP	328	Renzetti et al. (2025)	0.071

glassy state, their viscosities begin to diverge (Ollett and Parker, 1990). If $T_{g,s}$ values are accurately determined, plotting viscosity against T_g/T should yield overlapping curves.

To construct a reliable master curve for viscosity, we also included data for sucrose and trehalose, for which such a master curve has already been demonstrated by Longinotti and Corti (2008). Sucrose data from NBS (Swindells et al., 1958) serve as a reference due to their high accuracy. Following Van der Sman and Mauer (2019), we used $T_{g,s} = 336$ K for sucrose and $T_{g,s} = 388$ K for trehalose.

By fitting the T_2 -NMR data from Asghari et al. (2024) to the established trendline using least-squares regression, we estimated $T_{g,s} = 300.1 \pm 6.1$ K for glucose and $T_{g,s} = 286.4 \pm 3.7$ K for fructose. These estimates yield T_2 values that closely follow the trendline, as shown in the top panel of Fig. 2. The uncertainties were derived from the covariance matrix of the fit. Using these updated $T_{g,s}$ values, we replotted the viscosity data of glucose and fructose against T_g/T (bottom panel of Fig. 2), which now align well with the master curve defined by the disaccharide data. These results increase the confidence in the accuracy of the trend-line.

3.3. Analysis of new experimental data

Subsequently, we analyzed the new experimental data on carbohydrate solutions. The tested carbohydrate solutions are listed in table 3, together with their $T_{g,s}$ values used, as reported in the indicated references. The T_g values are computed using the listed $T_{g,s}$ values, mass fractions and Eq. (1). Their T_2 values versus T_g/T are shown in Fig. 3, together with the trend-line from Fig. 1.

We compare the new experimental data with the trend-line using a Root-Mean-Square-Error metric:

$$RMSE = \frac{\sum_i (\hat{y}_i - y_i)^2}{N} \quad (2)$$

With $y_i = \log(T_2)$, and \hat{y}_i its prediction based on the trendline. N is the number of datapoints per compound. The RMSE per compound is listed in Table 3.

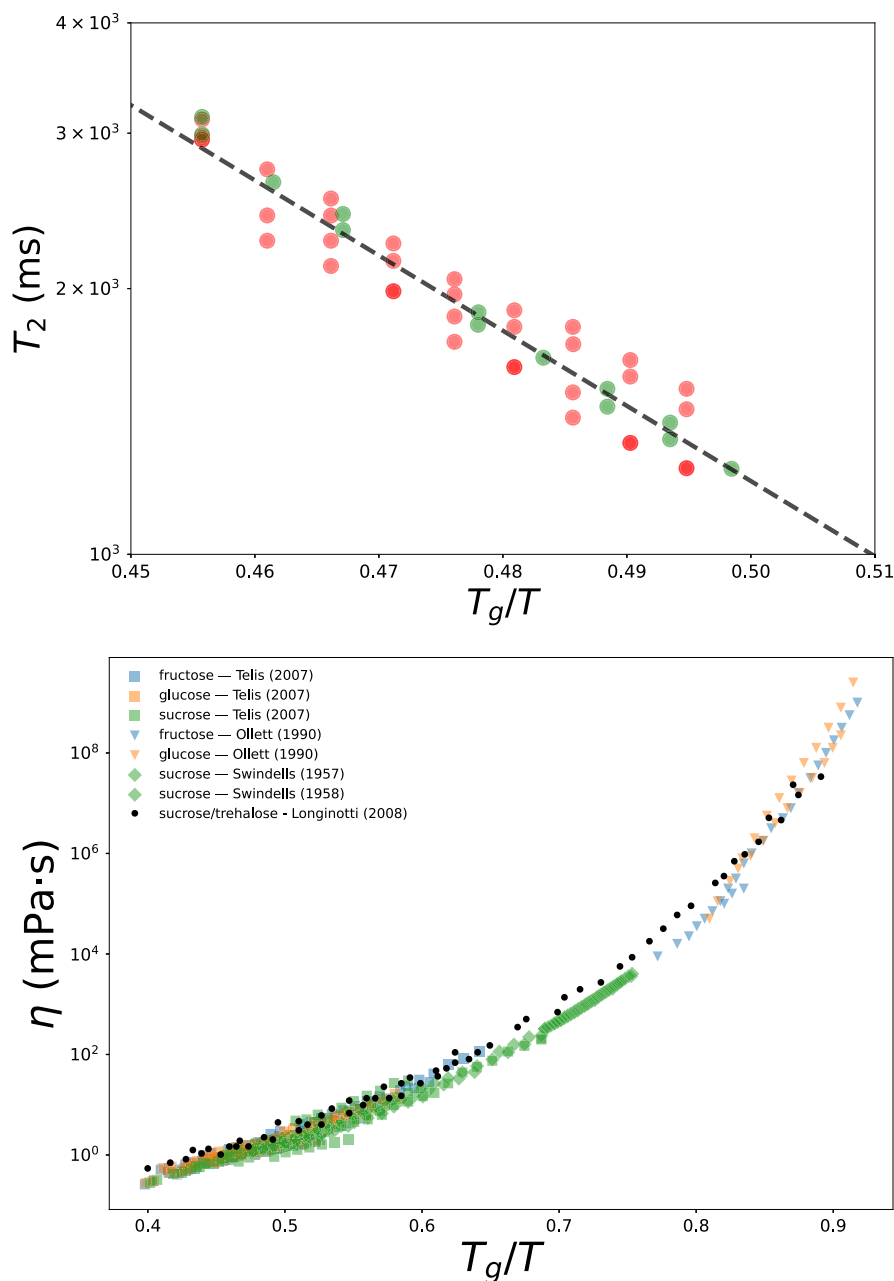


Fig. 2. Top: Correlation of T_2 relaxation time with T_g/T for glucose (red) and fructose (green) after their correction of $T_{g,s}$. Bottom: Master curve of viscosity from glucose, fructose, sucrose and trehalose as function of T_g/T , using the corrected $T_{g,s}$.

The RMSE shows that most of the data follow closely the trend line, but there are some strong deviations, especially for novel sugar replacers like Promitor and XOS, whose $T_{g,s}$ is not firmly established yet. Furthermore, in the new experimental data, there appears to be a systematic deviation from the trend-line, which possibly can be attributed to differences in field-strength of the NMR equipment, measurement protocol, or data-analysis techniques used by different sources. We think it is currently best practice to establish trendlines per NMR machine, using samples across the T_g/T regime, especially where $0.7 < T_g/T < 0.9$.

3.4. T_2 relaxation times of biopolymers

T_2 -NMR measurements of relatively large maltodextrins (with a dextrose equivalence $DE = 15$) have been reported by Ruan et al. (1998), who also measured the glass transition temperature of this compound

using DSC. The corresponding glass transition and NMR data, plotted against T_g/T , are shown in Fig. 4. Fitting the glass transition data using the Couchman–Karasz equation yielded a dry solute glass transition temperature of $T_{g,s} = 382$ K, which was used to compute the T_g/T values.

Due to the low moisture content ($y_w < 0.2$), the dominant NMR signal corresponds to the short spin-spin relaxation time, T_{2S} , associated with the mobility of carbohydrate protons (Li et al., 1996). These relaxation times are on the order of microseconds—significantly shorter than the T_2 values discussed in the previous section. This discrepancy may also stem from the data processing method used by Ruan et al. (1998), who fitted a sum of Gaussians to the raw signal rather than the more conventional sum of exponential decays applied to FID data.

Subsequently, we analyzed our own T_2 relaxation time data for maize flour and soy flour at varying moisture contents and temperatures. Assuming that the dry glass transition temperatures ($T_{g,s}$) of

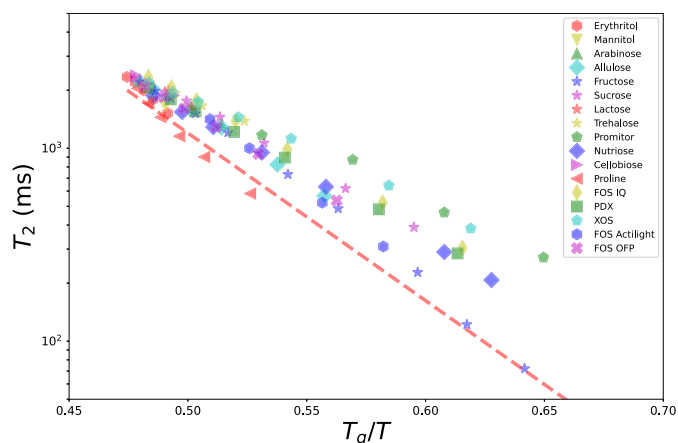


Fig. 3. Newly obtained experimental data of T_2 relaxation times of carbohydrate systems versus T_g/T , as compared to the trend line (red dashed line), as fitted to data of Fig. 1.

maize and soy flours are equivalent to those of pure starch (Van der Sman and Meinders, 2011) and pure soy protein van der Sman et al. (2023), we computed T_g using the Couchman–Karasz equation. The raw NMR signal was fitted using a bi-exponential decay model, yielding a short (T_{21}) and a long (T_{22}) relaxation time. The component with the shorter relaxation time, T_{21} , consistently exhibited the largest amplitude.

Our analysis shows that T_{21} and T_{22} are of similar magnitude for both maize and soy flour at comparable T_g/T values. Because of its lower amplitude, the T_{22} relaxation times are understandably more inaccurate (Callaghan, 1993). Still, the data for maize flour clearly exhibit a plateau in T_{22} at $T_g/T > 1$, consistent with the behavior observed in the literature.

These flours contain raw starches and cellulosic materials, part of which is assumed to be crystalline and thus non-hygroscopic, contributing neither to water absorption nor to the glass transition. We calibrated the degree of crystallinity such that the T_{22} plateau for maize flour aligns with $T_g/T = 1.05$. For soy flour, the degree of crystallinity was adjusted to align the T_{21} vs. T_g/T curves of both flours. The resulting calibrated degrees of crystallinity were $\zeta = 0.15$ for soy flour and $\zeta = 0.20$ for maize flour. Fig. 5 presents the results after this calibration.

From Fig. 5, we observe that the T_{21} values are comparable to the T_{2S} values of maltodextrin DE15, as discussed earlier. The slope of $\log(T_{21})$ versus T_g/T is nearly identical for maize and soy flour.

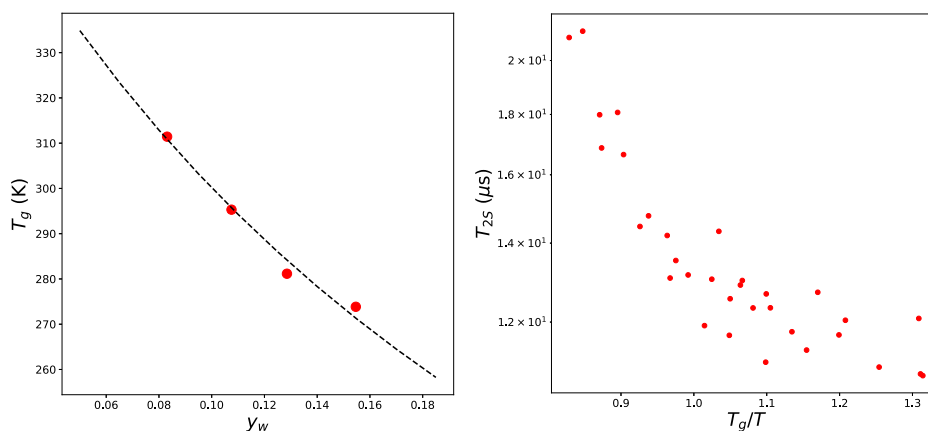


Fig. 4. Left pane shows the glass transition of maltodextrin, as measured by Ruan. The solid line indicated the fitting of the data with the Couchman–Karasz theory. The right pane shows the T_{2S} -relaxation time as function of T_g/T , with T_g computed using Couchman–Karasz with the given moisture content y_w .

Table 4

Glass transition temperature $T_{g,s}$ of fructose and glucose following literature.

Compound	$T_{g,s}$ (K)	Reference
Fructose	278	Constantin et al. (2016)
	284	Arvanitoyannis et al. (1993)
	287	Saavedra-Leos et al. (2012)
	280	Orford et al. (1990)
	286	Finegold et al. (1989)
	289	Simatos et al. (1996)
Glucose	304	Constantin et al. (2016)
	310	Saavedra-Leos et al. (2012)
	311	Orford et al. (1990)
	312	Finegold et al. (1989) Schugmann and Foerst (2022)
	314	Arvanitoyannis et al. (1993)

Interestingly, T_{22} also appears to correlate with T_g/T , despite the higher noise level. In particular, the soy flour data suggest a linear relationship between $\log(T_{21})$ and T_g/T in the range $T_g/T < 1$. Although the maize flour data are noisier, they also indicate a plateau in T_{22} at $T_g/T > 1$.

We must note that the investigated biopolymer systems are multi-component and semicrystalline, that was not fully characterized. The multicomponent character can lead to multiple peaks with different relaxation times, similar to the occurrence of multiple glass transitions in complex mixtures (Duval et al., 2016; Van der Sman, 2019). Peaks associated with different biopolymers as proteins, starch and cellulose may even overlap, given the similarity of relaxation times of soy and maize flours. Crystalline domains can still interact with water via hydrogen bonds (Kulasinski et al., 2015), which can lead to a new water population with their own relaxation time.

4. Conclusion

This study confirms the findings of Godefroid et al. (2023), demonstrating that T_2 relaxation time is a convenient and effective method for characterizing the plasticizing properties of sugar replacers. The relaxation time can be directly related to the hydrogen bond density $n_{OH,eff}$ or its associated parameter T_g/T , the ratio of the glass transition temperature to the actual temperature. For the range $T_g/T < 1$, we observed a universal linear relationship between $\log(T_2)$ and T_g/T , which holds across a wide range of plasticizers, including carbohydrate, pure water and proline solutions. For $T_g/T > 1.05$, the T_2 relaxation time reaches a constant, universal value.

For glucose and fructose, we tested the accuracy of T_2 NMR in determining the dry glass transition temperature $T_{g,s}$. By mapping T_2 values of sugar solutions at various concentrations onto the established T_2 vs. T_g/T trend line, we were able to estimate $T_{g,s}$ with an accuracy

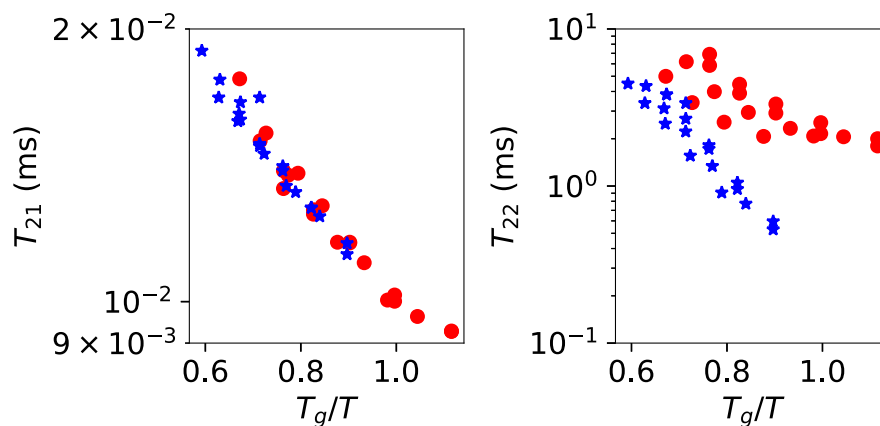


Fig. 5. Slow (T_{21}) and fast (T_{22}) NMR relaxation times of maize (red) and soy bean flours (blue) as function of T_g/T .

of 1%–2%. This demonstrates that T_2 NMR can be used as a rapid screening tool to estimate the plasticizing properties, glass transition temperature, and viscosity of novel sugar replacers. Moreover, T_2 NMR is well-suited for integration into high-throughput analytical platforms.

Similar trends were observed for biopolymeric systems, although the T_2 versus T_g/T curves do not overlap with those of small carbohydrate systems. Our findings suggest that while the underlying mechanism may be similar, the specific relaxation behavior may differ due to the more complex molecular architecture, and the semicrystallinity of biopolymers, and warrant further investigations.

Our findings also highlight the potential of T_2 NMR for determining T_g/T in biopolymeric systems, where this ratio is a key parameter governing rheological behavior. However, the current dataset is insufficient to construct a universal master curve, as was achieved for small carbohydrate systems. A promising direction for future research is the study of complex mixtures of biopolymers, water, and secondary plasticizers such as sugars. These systems are prone to phase separation, and the impact of such phenomena on rheology remains poorly understood. We propose that T_2 NMR could serve as a valuable tool for elucidating these effects.

CRedit authorship contribution statement

Ruud van der Sman: Conceptualization – Writing: first draft; editing + review – Data Analysis. **Stefano Renzetti:** Funding acquisition, Writing – editing + review. **Panos Voudouris:** Data Analysis. **Ali Asghari:** Data curation. **Seddik Khalloufi:** Funding acquisition, Writing – editing + review.

Declaration of competing interest

Authors declare there is no conflict of interest

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