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Grau en
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Treball Final de Grau

Determination of thermodynamic properties of D-sorbitol dehydration to produce D-isosorbide

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When you tear out a man's tongue, you are not proving him a liar, you're only telling the world that you fear what he might say.

Tyrion Lannister

En primer lloc m'agradaria agrair als meus tutors del treball final de grau, Dra. Eliana Ramírez i Dr. Javier Tejero, per haver-me donat la oportunitat de treballar en un projecte tant innovador com aquest i per haver-me ajudat en tot moment des del primer dia.

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CONTENTS

SUMMARY

This work concerns the synthesis of the compound isosorbide which is a product with a wide range of applications in the industry. One of the most interesting applications from an environmental point of view is its use for the synthesis of polymers as a replacement of fossil derivates such as bisphenol A. Processes like this have recently gained a lot of interest due to environmental issues that concern society. Therefore, the study and development of alternative renewable energy processes to reduce the environmental impact of the industries is of great importance.

The present work studies the thermodynamics of the double dehydration reaction of sorbitol to isosorbide. A series of group contribution methods have been considered in order to estimate the thermodynamic parameters of the compounds involved in reaction network. These parameters have been used to determine the equilibrium constant of each reaction and have been compared to two other non-experimental studies.

The thermodynamic analysis shows a discrepancy between the studies, on whether the dehydration of sorbitol reactions are endothermic or exothermic, and consequently on the magnitude of the equilibrium constants.

Keywords: Isosorbide, sorbitol, D-glucitol, thermodynamic parameters determination, green chemistry.

RESUM

Aquest estudi està relacionat amb la síntesi del compost isosorbida, un producte amb àmplies aplicacions a nivell industrial. Una de les aplicacions més interessants des del punt de vista mediambiental és el seu ús com a substitut de derivats del petroli, com el bisfenol A, per a la síntesi de polímers. Processos com aquest han guanyat interès en els darrers anys degut a la preocupació mediambiental present a l'actualitat, i per tant és de gran importància l'estudi i desenvolupament de processos alternatius que utilitzin fonts d'energia renovables.

Aquest treball estudia la termodinàmica de la doble deshidratació del sorbitol a isosorbida. S'han considerat una sèrie de mètodes de contribució de grups per a estimar les propietats termodinàmiques dels compostos involucrats en la xarxa de reaccions. Aquests paràmetres s'han utilitzat per a la determinació de les constants d'equilibri de cada reacció i posteriorment s'han comparat amb els resultats de dos estudis no experimentals.

L'anàlisi termodinàmic mostra una discrepància entre els estudis sobre si les reaccions de deshidratació del sorbitol són endotèrmiques o exotèrmiques, i conseqüentment, sobre la magnitud de les constants d'equilibri.

Paraules clau: Isosorbida, sorbitol, D-glucitol, determinació de paràmetres termodinàmics, química verda.

1. INTRODUCTION

1.1. BIOPLASTICS

Nowadays humanity is facing a large number of issues related to energy, environment and scarcity of water and resources. All the waste humans and the industry generate is undoubtedly making a huge impact on our planet, and if we do not make severe changes, irreversible consequences might happen in the near future.

The use of plastics is one of the main concerns due to the depletion of fossil resources. Some industries have already moved towards the synthesis of alternative polymers based on biomass. 1.5 % of the total plastics produced in 2016 were bioplastics [1]; however, this figure remains anecdotal. Hence, it is of great importance to keep innovating on this field because bioplastics would not only be an excellent replacement for fossil-based plastics, but also would guarantee a more sustainable development.

Bio-based polymers are, by definition, all plastics derived from renewable carbon sources such as biomass. Biomass consists primarily of lignocellulose which is mainly made of lignin, hemicellulose, and cellulose. Since lignocellulose is the most abundant raw material available on Earth, its use as a source of sustainable materials is very promising. Moreover, through fermentation and chemical transformations, lignocellulose residues could lead to a great deal of added-value products like ethanol, lactic acid, furans, glycerol, levulinic acid and sorbitol which has been identified by the US Department of Energy as one of the ten more promising bio-based building blocks for the chemical industry [2].

1.2. **SORBITOL**

Sorbitol, also known as D-glucitol or D-sorbitol, is a sugar alcohol formed by a six-carbon chain and six alcohol groups (Figure 1) being an isomer of mannitol. It is one of the main photosynthetic end products and serves as a storage and transport sugar in most plant families [3].
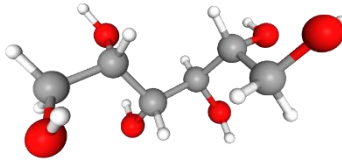
Figure 1: Sorbitol molecule 3D structure

The main natural route to obtain sorbitol is by the reduction of glucose. It is synthesized from glucose 6-phosphate first by the enzyme sorbitol-6-phosphate dehydrogenase (S6PDH) and then sorbitol-6-pyrophosphatase (S6PP) (Figure 2).
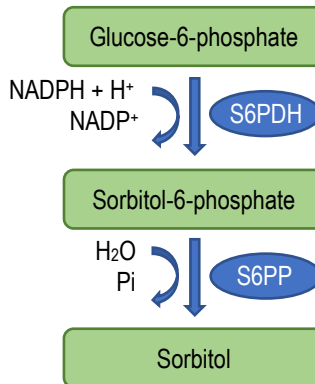
Figure 2: Natural synthesis of sorbitol from glucose-6-phosphate. Based on a scheme from Resham Sharma et al. [3]

Sorbitol has plenty of industrial applications, especially in the food industry. It is used as a sugar substitute being 60% as sweet as sucrose [4]. It is added in a wide range of products including baked goods, confectionary, fruit preserves and specifically in food for diabetics since blood glucose does not increase when consumed. In addition, sorbitol has been used as a "sugar-free" ingredient in food and related products for over 50 years [5].

Sorbitol is also used in the field of medicine, often used in cosmetics like lotions or face creams as a humectant and thickener. Furthermore, it is widely used in oral hygiene formulation industries due to its resistance to fermentation by dental plaque bacteria [6].

1.3. **ISOSORBIDE**

Isosorbide is an organic compound from the group of diols containing two fused furan rings in its structure, shown in Figure 3. It is a white, crystalline, highly hydrophilic solid at standard state conditions.
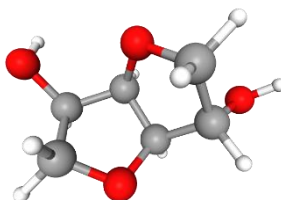

Figure 3: Isosorbide molecule 3D structure

Isosorbide is commonly used in pharmaceutical industry. By nitration of isosorbide, the nitrates compounds obtained gain vasodilator activity which relaxes vascular smooth muscle by formation of nitric oxide radicals [7]. It is also used as a diuretic to treat hydrocephalus and glaucoma [8]. In addition, isosorbide is widely used as a drug, being the 101st most prescribed medication in the U.S.A in 2016 with over 7 million prescriptions [9].

Besides the pharmaceutical industry, the use of isosorbide as component to form polymers is probably the most attractive. Some companies like Mitsubishi Chemical or Teijin have already commercialized some isosorbide-based polycarbonates like DURABIO® and PLANEXT®. Other strategies use isosorbide as a substituted of ethylene glycol, which is presently used for the synthesis of polyethylene terephthalate (PET), forming polyethylene isosorbide terephthalate (PEIT) [10]. Not only are some of these bioplastics more sustainable than general plastics, but also have better physical properties such as improved stiffness and heat resistance.

Isosorbide is produced industrially on 10^4 tons scale per year using a three-stage process starting with the depolymerization of starch feedstock into glucose monomer, which is then hydrogenated to form sorbitol, and finally doubly dehydrated into isosorbide. Although starch is the main source to obtain isosorbide, alternative resources are being studied that do not compete with the food chain. The main candidate that has been taken into consideration is cellulose, as it is an abundant biopolymer available in large scale from the agricultural sector [10].

Isosorbide is one of the interesting compounds that can be obtained from (ligno)cellulose. This process is characterized by a three-step reaction (Figure 4): 1) hydrolysis of cellulose or lignocellulose to glucose 2) hydrogenation of glucose to form sorbitol 3) dehydration of sorbitol to isosorbide.
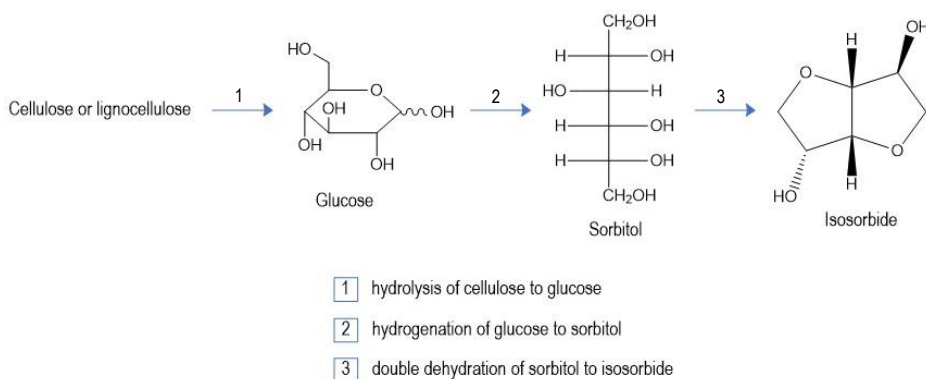

1	hydrolysis of cellulose to glucose
2	hydrogenation of glucose to sorbitol
3	double dehydration of sorbitol to isosorbide

Figure 4: Isosorbide synthesis steps from cellulose or lignocellulose

In the first step, is reported to be using acids like H_2SO_4, H_3PO_4 and HCl as catalysts as well as heterogeneous catalysts tungstolitic acid ($H_4SiW_{12}O_{40}$), niobium phosphate, Amberlyst-70, and Dowex-H [11]. In the hydrogenation of glucose, it is usually used Ni- and Ru- based catalysts [10]. Then sorbitol is dehydrated through an acid-catalyzed process which will be further explained in this work.

In the conversion of sorbitol to isosorbide, a double dehydration occurs. Firstly, the dehydration of sorbitol leads to the formation of the intermediates 1,4-sorbitan and 3,6-sorbitan, and secondly, these intermediates are dehydrated to the final product isosorbide. Moreover, some side-products such as the constitutional isomers 1,5-sorbitan or 2,5-sorbitan might be formed when sorbitol is dehydrated (Figure 5).
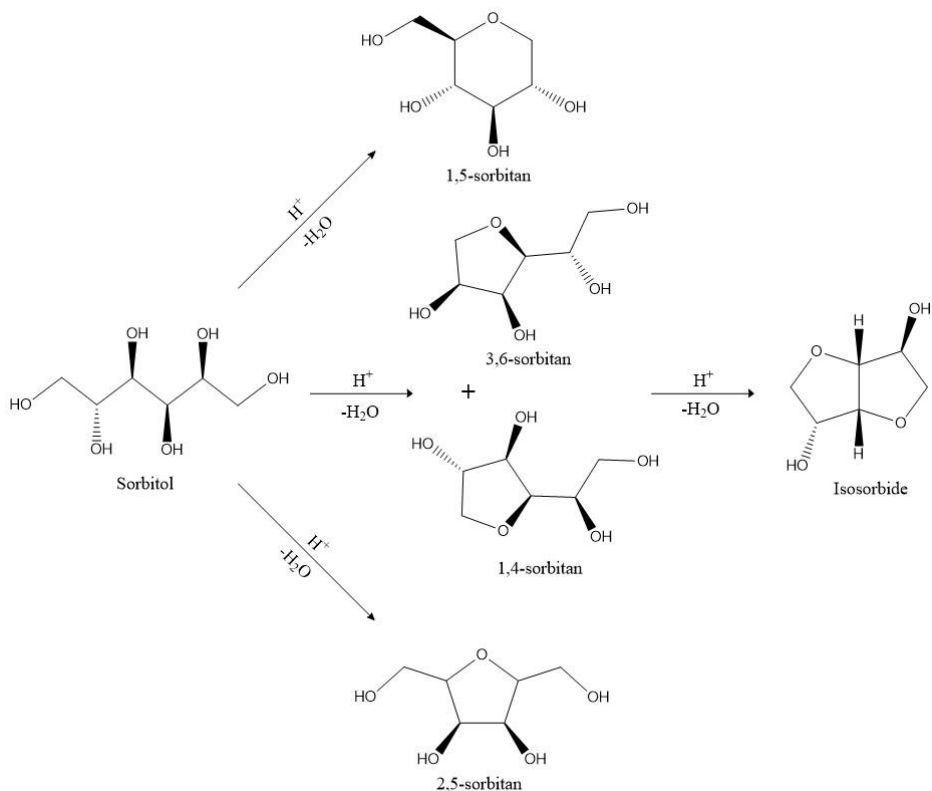
Figure 5: Sorbitol double dehydration to Isosorbide and side products 1,5-sorbitan and 2,5-sorbitan

Hence, in order to avoid the formation of these non-desired compounds a set of parameters must be considered, such as the conditions in which the reaction takes place, pH, time of reaction or type of catalyst.

1.4. THE USE OF CATALYSTS

As mentioned in the previous section, one of the main factors that influence the yield of isosorbide is the catalyst. Thus, a lot of research has been done in the last two decades on how both homogeneous and heterogeneous acid catalysts and its acidity affect the conversion of isosorbide. For instance, Aasif A. Dabbawala et al. pointed out that catalytic activity and yield of isosorbide evolve together depending on pKa value of the selected acid catalyst and that the

nature of the catalyst and its acidic strength influence the formation of side products. On the one hand, it was also shown that acid catalysts presenting pKa values < 1 are able to produce high yields of isosorbide (60-70 %) at temperatures around 160 ºC after 60 min of stirring. On the other hand, by using acid catalysts with a pKa value > 1, the catalyst activity and the isosorbide formation tend to decrease gradually in concert with the increase of pKa value [10]. Furthermore, a comparison between Bronsted and Lewis acids was made, and it was manifested that Bronsted acids are more efficient at converting sorbitol to isosorbide than Lewis acids since they have a lower pKa values and therefore a greater catalyst activity. Additionally, Lewis acids' catalytic activity seemed to be radically dependent on whichever metal was used and their stability during the reaction.

Homogeneous catalysts are generally used to produce isosorbide from sorbitol since they acquire a good catalytic activity. However, the large-scale use of homogeneous catalysts presents some drawbacks such as equipment corrosion, formation of side products and hence, difficulties on separating the final product. In contrast, heterogeneous catalytic systems seem to be an ideal alternative for the industry. Consequently, numerous scientists have made research in the design of novel solid catalysts. Khan et al., for example, obtained 61% of isosorbide selectivity within 2h at 201 ºC using 0.5 g of sulphated zirconia as catalyst [10]. The use of heterogeneous catalysts also presents some disadvantages like the dependence of the yields of both sorbitans and isosorbide on the adsorption strength due to the hydrophilic-lipophilic equilibrium observed on the surface.

Researchers have also studied the possibility of conducting the cellulose conversion to isosorbide in a one-pot step. Isaline Bonnin et al. compared numerous studies conducted by various scientists who performed some experiments on a laboratory scale using different catalysts. It was shown that Ru/C was the most active catalyst in the hydrogenation reaction. However, it was concluded that even though one step conversion of cellulose is attractive, the overall yields obtained were not entirely favourable as the conditions required for a one-step conversion facilitate the deactivation of the hydrogenation catalysts [11].

2. OBJECTIVES

The aim of the present work is to study the thermodynamics of the reaction network involved in the synthesis of isosorbide from sorbitol.

A series of group contribution methods will be employed to estimate the thermodynamic properties of the compounds involved in the reactions. Those estimated properties will then be used to obtain a mathematical expression that relates the equilibrium constant to the temperature. Moreover, the equilibrium constants as well as the enthalpies of some reactions will be compared to a similar study that has been recently published.

3. THEORETICAL FRAMEWORK

The equilibrium constant (K) is defined as the relationship at the chemical equilibrium between the amount of products and reactants that intervene in a reversible chemical reaction.

Considering a system undergoing a reversible reaction, the general chemical reaction is
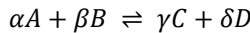
$$\alpha A + \beta B \rightleftharpoons \gamma C + \delta D$$

where A and B are reactants, C and D are products, and α, β, γ and δ are the stoichiometric coefficients. Since it is a reversible reaction, two reactions take place simultaneously:

$$\alpha A + \beta B \rightharpoonup \gamma C + \delta D \qquad r_d = k_d C_A{}^\alpha C_B{}^\beta \qquad (1)$$

$$\gamma C + \delta D \rightharpoonup \alpha A + \beta B \qquad r_i = k_i C_C{}^\gamma C_D{}^\delta \qquad (2)$$

where k_d is the reaction rate coefficient of the forward reaction, k_i is the reaction rate coefficient of the backward reaction, C_j are the molar concentrations of the compound j, r_d is de rate of the forward reaction and r_i for the reverse reaction. Equations 1 and 2, however, are satisfied when the reactions are elemental, and the reaction rate is expressed by the law of mass action.

Since it is a reversible reaction, at chemical equilibrium the rates of both reactions are equal but opposite sign:

$$(3)$$

$$r_d = -r_i$$

The fundamental expression of the equilibrium constant is the following:

$$K_a = \frac{a_C{}^\gamma a_D{}^\delta}{a_A{}^\alpha a_B{}^\beta} \qquad (4)$$

where a_j is the activity of the compound j. Although the thermodynamical definition of the equilibrium constant is function of the activities, it is usually approximated to the molar concentrations (K_c):

$$K_c = \frac{C_C{}^\gamma C_D{}^\delta}{C_A{}^\alpha C_B{}^\beta} \qquad (5)$$

It is often expressed in terms of partial pressures (p_j) for gaseous reactions (K_p):

$$K_p = \frac{p_C{}^\gamma p_D{}^\delta}{p_A{}^\alpha p_B{}^\beta} \tag{6}$$

The thermodynamic definition relates the equilibrium constant at standard state conditions (298,15 K and 1 atm), the Gibbs energy ($\Delta G^o(T)$) and the temperature:

$$\ln(K) = -\frac{\Delta_r G^o(T)}{R\,T} \tag{7}$$

It can also be represented by the state functions enthalpy $\Delta H^o(T)$ and entropy changes of reaction $\Delta S^o(T)$ in the equation below.

$$\Delta G^o(T) = \Delta H^o(T) - T\Delta S^o(T) \tag{8}$$

$$\ln(K) = -\frac{\Delta_r H^o(T)}{R\,T} + \frac{\Delta_r S^o(T)}{R} \tag{9}$$

where T is the temperature in K and R is the gas constant in J/(mol·K). Through equation 9 the temperature dependency of the constant of equilibrium is expressed as an exponential function, in fact, for endothermic reactions the value of the constant increases when the temperature is risen.

The enthalpy of reaction can be calculated through the enthalpy of formation of the compounds involved in the reaction through the following equation:

$$\Delta_r H^o(T) = \sum_{j=1} \nu_j \cdot \Delta_{f_j} H^o(T) \tag{10}$$

where ν_j is the stoichiometric coefficient of the species j participant in the reaction. The value of the stoichiometric coefficient is positive ($\nu_j > 0$) for the products, and negative for the reactants ($\nu_j < 0$). Moreover, $\Delta_{f_j} H^o$ is the enthalpy of formation in kJ/mol of the compound j, and is the change of enthalpy during the formation of 1 mol of the compound from its constituent elements.

Similarly for the entropy of reaction, whose expression is the following:

$$\Delta_r S^o(T) = \sum_{j=1} \nu_j \cdot S_j{}^o(T) \tag{11}$$

where $S_j^{\,o}(T)$ is the molar entropy in J/(mol·K) of the compound j at a temperature T.

When the reaction is carried out in non-standard conditions and the enthalpies of formation are unavailable at the temperature of the reaction, the Kirchhoff's equation (equation 12) needs to be applied.

$$\Delta_r H^o(T) = \Delta_r H^o(T_0) + \int_{T_0}^{T} \sum_{i=1} \nu_i \cdot c_{p_i}(T) dT \tag{12}$$

Same happens with the entropy:

$$\Delta_r S^o(T) = \Delta_r S^o(T_0) + \int_{T_0}^{T} \frac{\sum_{j=1} \nu_i \cdot c_{p_j}(T)}{T} dT \tag{13}$$

where c_{p_j} is the heat capacity of the substance j and depends on the temperature. Whether state change occur, the enthalpy of that state change need to be summed to the equation, and the heat capacities must be used in the adequate state depending on the range of temperatures in which the reaction is being evaluated.

In the present work the reactions presented in Figure 6 are considered.
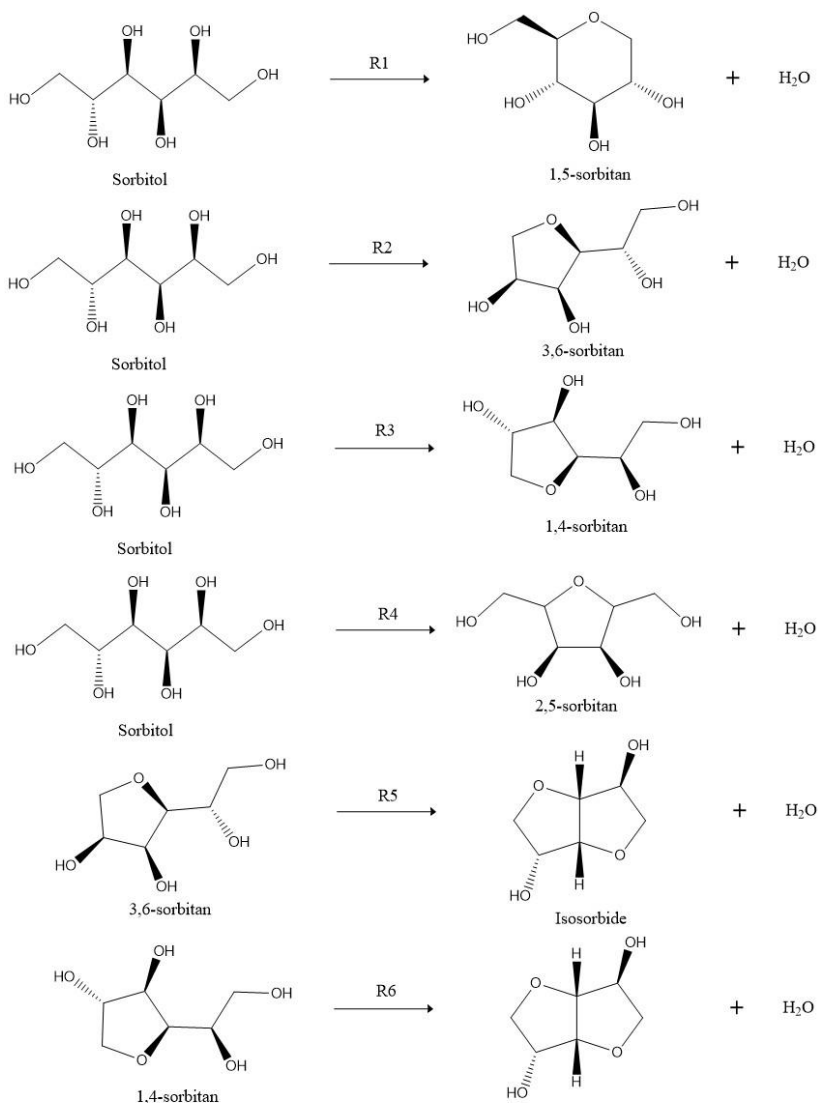
Figure 6: Studied reactions in the present work

From now on, the reactions will be referred to as R_i to simplify the reading.

4. ESTIMATION OF THE THERMODYNAMIC PROPERTIES

In order to estimate the equilibrium constant, some thermodynamic properties of the compounds that take part in the reactions need to be obtained. In addition, a series of group contribution methods will be employed to get an approximate value of these parameters. These methods sum up all the little contributions of each bond between the atoms of the molecules and are rather useful for those species whose thermodynamic properties have not been yet experimentally determined.

4.1. METHOD OF DOMALSKI AND HEARING

Sidney W. Benson was a distinguished American chemist who made exceptional advances in the thermochemistry field [12]. Together with his research team developed a group contribution method in the late 60's that allows calculating some properties such as enthalpy of formation, entropy, or heat capacities for mainly C-H-O-N-S molecules in the gas phase at 298,15 K and 1 atm. Furthermore, in the early 90's Domalski and coworkers, especially Domalski and Hearing, modified the method with the purpose of enabling the estimation of the properties for condensed phases [13].

Since the double dehydration reaction takes place in liquid phase, Domalski and Hearing method will be employed to estimate the enthalpy and entropy of formation of the compounds except for water, whose properties will be taken from the Nation Institute of Standards and Technology (NIST) [14].

The enthalpy of formation at standard conditions in the liquid phase can be estimated with the following equation:

$$\Delta_f H^o (298.15\ K) = \sum_k N_k \cdot \Delta_{fk} H^o \qquad (14)$$

where N_k is the number of groups of type k and $\Delta_{fk}H^o$ is the enthalpy of formation of the type k group. The enthalpies of formation of each group are obtained from tabulated values which were estimated from available experimental values of enthalpy of formation of a variety of compounds.

Entropy is calculated similarly by equation 15.

$$\Delta_f S^o(298.15\ K) = \sum_k N_k \cdot \Delta_{fk}S^o + S_s^o \tag{15}$$

where N_k is the number of groups of type k, $\Delta_{fk}S^o$ is the entropy of the type k group which are also obtained from tabulated values, and S_s^o is a value related to the symmetry of the molecule that needs to be summed. This symmetry correction has been the source of some difficulty throughout the development of this study due to the complexity of the molecular structure of the compounds involved in the reactions.

S_s^o (J/(mol·K)) is divided into two parameters:

$$S_s^o = R \cdot (\ln \eta - \ln \sigma) \tag{16}$$

where η is the number of optical isomers that the molecule has, and σ is defined according to Benson as "the total number of independent permutations of identical atoms (or groups) in a molecule that can be arrived at by simple rigid rotations of the entire molecule". Inversion is not allowed [15].

It is recommendable to split σ into σ_{ext} and σ_{int} so that:

$$\sigma = \sigma_{ext}\sigma_{int} \tag{17}$$

where σ_{ext} and σ_{int} are the two distinct types of indistinguishability that can occur, external and internal respectively. In order to make a better description of these parameters, propane will be considered as an example; σ_{int} can be found by rotating terminal groups about their bonds to internal groups. Propane has two terminal methyl groups (-CH₃) which have a threefold axis of symmetry; thus, its value will be $\sigma_{int} = 3^2$. On the other hand, σ_{ext} comes from indistinguishability when the entire molecule is rotated as if it was rigid, so its value for propane will be $\sigma_{ext} = 2$.

Taking for instance isosorbide, the procedure to note is the following:

Firstly, the tabulated values need to be taken for every single group that appear in isosorbide molecular structure (Table 1). The tabulated values used for the other compounds are included in Appendix 1. These values have been extracted from Domalski and Hearing's article [13].

Table 1: Isosorbide constituent groups for Domalski and Hearing method
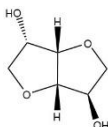
| Group | N_k | Isosorbide | |
		$\Delta_f H°$ [kJ/mol]	$S°$ [J/(mol·K)]
O-(H)(C)	2	-191.5	43.89
C-(H)₂(C)(O)	2	-35.8	32.59
C-(H)(C)₂(O)	4	-27.6	-29.83
O-(C)₂	2	-110.83	26.78
THF rsc	2	17.7	47.18

Notice that in Table 1 appear a *THF rsc* group which stands for tetrahydrofuran ring strain correction. Domalski and Hearing's method takes into account whether the compounds own a ring in their structure, and if that is the case a little correction is applied due to the fact that the way atoms are bonded may also affect their properties.

For the sake of simplicity, since the 1,5-sorbitan tetrahydropyran ring strain correction (THP rsc) in the liquid phase is unknown, it has been estimated. The procedure to do so has been using the proportion of THF rsc liquid and gas values and extrapolating this proportion to the THP rsc values (equation 46 in Appendix 1).

Secondly, the symmetry entropy (S_s^o) for isosorbide has been determined as followed:

To obtain the number of optical isomers of the molecule (η), the number of asymmetric carbon atoms must be counted. Isosorbide has 4 asymmetric carbon atoms, marked in red in Figure 7.
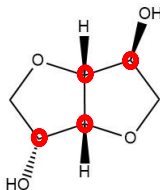
Figure 7: Asymmetric carbon atoms of isosorbide marked in red

Once the asymmetric carbon atoms have been spotted, the maximum possible isomers are calculated with 2^n, n being the number of asymmetric carbon atoms. Hence the maximum possible isomers for isosorbide are $2^4 = 16$, which are represented in Figure 8.
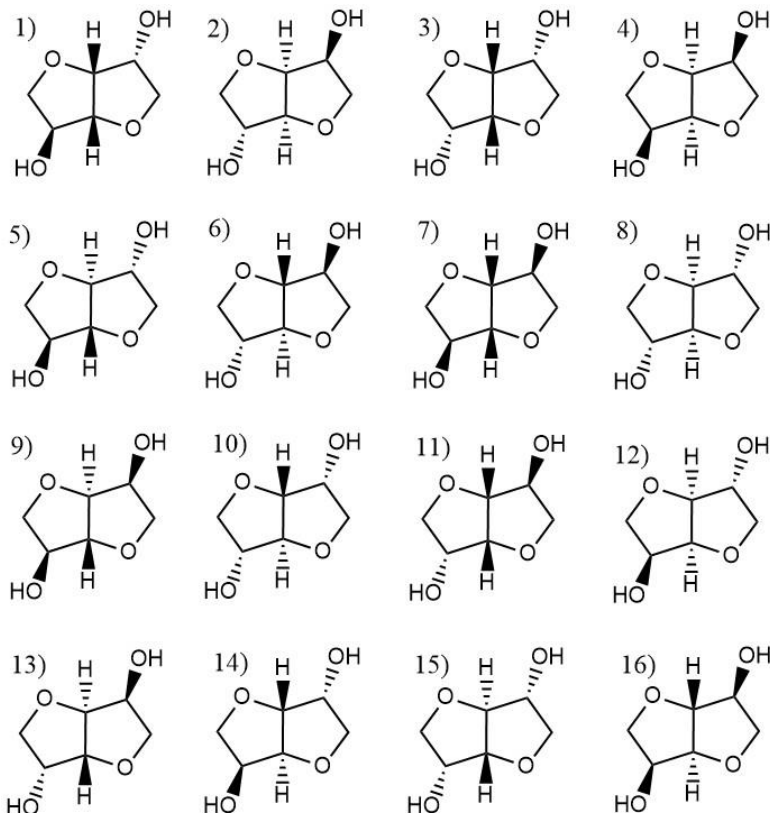
Figure 8: Possible isomers of isosorbide drawn with ChemDraw

Once the molecules are drawn, the possible planes of symmetry which negate the optical activity of some forms like meso form must be subtracted. Although these conformations apparently seem all different, some of them are the same; 1 and 11, 2 and 12, 5 and 6, 9 and 16, 10 and 15, 13 and 14. By rotation, one will see that these pair of molecules are equal. Hence, between these 16 conformations only 10 are optical isomers, so $\eta = 10$.

In the case of isosorbide both σ_{ext} and σ_{int} equal 1 since isosorbide do not present indistinguishable configurations, so $\sigma = 1$. Using equation 16, the symmetry entropy equals $S_s^o = 19.14 \, J/(mol \cdot K)$, which must be summed to the total entropy. It is noteworthy that the obtention of σ has not been clear due to the complexity of the molecules. Hence, the values that have been estimated, shown in Table 2, are likely to be rather deviated.

Table 2: Symmetry and isomeric parameters of each molecule used to determine the symmetry entropy

Compound	σ_{int}	σ_{ext}	σ	η	S_s° [J/(mol·K)]
Sorbitol	1	1	1	10	19.14
1,4-sorbitan	1	1	1	16	23.05
3,6-sorbitan	1	1	1	16	23.05
Isosorbide	1	1	1	10	19.14
1,5-sorbitan	1	1	1	16	23.05
2,5-sorbitan	1	2	2	9	12.51

As mentioned previously, the values are not entirely reliable.

Finally, equations 14 and 15 are used to calculate the enthalpy of formation and entropy of isosorbide at 298.15 K and 1 atm, resulting into the values shown in Table 3.

Table 3: Enthalpies and entropies of formation at 298.15 K and 1 atm of the compounds of the reaction system determined by Domalski and Hearing's method

Compound	Δ_fH [kJ/mol]	Δ_fS [J/(mol·K)]
Sorbitol	-1331.00	228.34
1,4-sorbitan	-1041.13	218.43
3,6-sorbitan	-1041.13	218.43
Isosorbide	-751.26	200.70
1,5-sorbitan	-1057.51	206.31
2,5-sorbitan	-1041.13	207.89

4.2. METHOD OF JOBACK

Another group-contribution method is the Joback method, often called Joback/Reid method. This method enables to estimate a great variety of thermodynamic parameters of hydrocarbon compounds in the gas phase at standard state conditions. Some of these parameters are the enthalpy of formation, the entropy, boiling temperature, critical temperature, critical pressure, and heat capacity [15]. Since this method is for the gas phase, Vetere method is proposed to convert the estimated properties into the liquid phase.

The enthalpy of formation at standard conditions in the gas phase is calculated by using equation 18:

$$\Delta_f H^o (298.15 \ K) = 68.29 + \sum_k N_k \cdot (hfk) \tag{18}$$

where N_k is the number of groups of type k and hfk is the enthalpy of formation of the k group in kJ/mol.

To apply Vetere method, the boiling temperature (T_b), the critical temperature (T_c) and the critical pressure (P_c) are needed. These variables can also be estimated using the Joback method through the following expressions:

$$T_b = 198 + \sum_k N_k \cdot (tbk) \tag{19}$$

$$T_c = T_b \left[0.584 + 0.965 \left\{ \sum_k N_k \cdot (tck) \right\} - \left\{ \sum_k N_k \cdot (tck) \right\}^2 \right]^{-1} \qquad (20)$$

$$P_c = \left[0.113 + 0.0032 N_{atoms} - \sum_k N_k \cdot (pck) \right]^{-2} \qquad (21)$$

Where tbk is the boiling temperature of the k group in Kelvin, tck is the critical temperature of the k group in Kelvin, pck is the critical pressure of the k group in bar, and N_{atoms} is the number of atoms of the molecule that is being evaluated.

Applying the method to isosorbide, the values to consider are shown in Table 4. The values for the other compounds can be found in Appendix 2.

Table 4: Isosorbide constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		Isosorbide			
OH (1)	2	-208.04	92.88	0.0741	0.0112
O(ss) (2)	2	-138.16	31.22	0.0098	0.0048
CH₂(ss) (2)	2	-26.80	27.15	0.01	0.0025
CH(ss) (3)	4	8.67	21.78	0.0122	0.0004

See that the nomenclature of the constituent groups differs from Domalski and Hearing's. In Joback's method, the bonds formed by atoms which are forming a ring get specific values. If the atom is part of an aromatic ring a (ds) is indicated next to the atom, on the contrary, if it is part of a nonaromatic ring a (ss) is indicated. Moreover, the number of other groups that each group is bonded to is given in parenthesis.

The results obtained for each compound are shown in Table 5.

Table 5: Estimated values of enthalpy of formation at 298 K and 1 atm in the gas phase, boiling and critical temperature and critical pressure of the species by Joback's method

Compound	Δ_fH_{gas} [kJ/mol]	N_{atoms}	T_b [K]	T_c [K]	P_c [bar]
Sorbitol	-1101.67	26	888.0	1092.9	68.3
1,4-sorbitan	-893.57	23	737.9	913.3	58.0
3,6-sorbitan	-893.57	23	737.9	913.3	58.0
Isosorbide	-643.03	20	587.6	776.9	52.2
1,5-sorbitan	-914.79	23	737.9	914.3	56.6
2,5-sorbitan	-908.63	23	733.6	907.1	54.5

4.3. VETERE METHOD

Vetere method is useful to estimate the enthalpy of vaporization at normal boiling point [15]. Thus, by subtracting the heat of vaporization to the enthalpy of formation at gas phase, an approximate value of the enthalpy of formation at liquid phase can be obtained (equation 24).

Enthalpy of vaporization ($\Delta_{vb}H$ in J/mol) at the normal boiling point is calculated with the following equation:

$$\Delta_{vb}H = RT_b \frac{(1 - T_{br})^{0.38}(ln\, P_c - 0.513 + 0.5066/(P_cT_{br}^2))}{1 - T_{br} + F(1 - (1 - T_{br})^{0.38})\ln\, T_{br}} \tag{22}$$

where T_{br} is the quotient between the boiling temperature and the critical temperature (T_b/T_c) and F is 1.05 for C_2 + alcohols and dimerizing compounds such as SO_3, NO and NO_2. For the rest of compounds, including the studied in this work, F is 1.

The enthalpy of vaporization is required to be converted to the standard temperature (298.15 K) since the one obtained in Vetere method is estimated at the boiling point. That can be done by applying Watson's ratio (equation 23), which is a widely used correlation.

$$\Delta_{vo}H = \Delta_{vb}H \left(\frac{1 - T_{ro}}{1 - T_{rb}}\right) \tag{23}$$

where $\Delta_{vo}H$ is the enthalpy of vaporization at 298.15 K in J/mol, T_{ro} is the quotient between T_o (298.15 K) and T_c, and T_{rb} is the division between T_b and T_c.

Once the enthalpies of vaporization are calculated the enthalpy of formation at standard state conditions in the liquid phase can be estimated by using the following expression:

$$\Delta_f H_{liquid}(T_o) = \Delta_f H_{gas}(T_o) - \Delta_{vo}H \tag{24}$$

The results obtained for each compound are shown in Table 6.

Table 6: Enthalpies of vaporization at boiling point and 298.15 K and enthalpy of formation in the liquid phase of each compound obtained by Vetere method

Compound	$\Delta_f H_{gas}$ [kJ/mol]	$\Delta_{vb}H$ [kJ/mol]	$\Delta_{vo}H$ [kJ/mol]	$\Delta_f H_{liquid}$ [kJ/mol]
Sorbitol	-1101.67[a]	162.06	271.25	-1372.92
1,4-sorbitan	-893.57[a]	125.83	202.69	-1096.26
3,6-sorbitan	-893.57[a]	125.83	202.69	-1096.26
Isosorbide	-643.03[a]	77.39	110.11	-753.14
1,5-sorbitan	-914.79[a]	124.49	200.25	-1115.04
2,5-sorbitan	-908.63[a]	123.52	199.05	-1107.68

(a) Values taken from Table 5 in Joback's method.

4.4. RŮŽIČKA AND ZÁBRANSKÝ METHOD

Another parameter that needs to be determined in order to apply equation 12 and 13 is the heat capacity as a function of temperature of every compound. In 1993, Růžička and Domalski developed a method valid for pure organic liquids which was based on the second order additivity scheme proposed by Benson and co-workers for ideal gases [16]. As well as the other methods, it consists in dividing the molecules into little groups formed by few bonds and then sum up the contribution of each group to obtain an approximation of the heat capacity.

Equation 25 is used to calculate the heat capacity of liquids in J/(mol·K):

$$C_{pL} = R \left[A + B \left(\frac{T}{100} \right) + D \left(\frac{T}{100} \right)^2 \right] \tag{25}$$

where R is the gas constant (8.314472 J/(mol·K)), T is the temperature in K and A, B [K^{-1}] and D [K^{-2}] are parameters of the function that differ between compounds.

The following equations are used to obtain these parameters:

$$A = \sum_{j=1}^{K} n_j a_j \qquad (26)$$

$$B = \sum_{j=1}^{K} n_j b_j \qquad (27)$$

$$D = \sum_{j=1}^{K} n_j d_j \qquad (28)$$

where n_j is the number of groups of type j, k is the total number of different type of groups, and a_j, b_j and d_j are parameters which are characteristic of each group. These parameters can be estimated by correlating experimental heat capacities by a minimization of a function. In this study, however, the value of these parameters will be taken from previous works.

Taking Isosorbide as an example, the parameters needed in equations 26-28 are expressed in the Table 7. Although the method is based on Růžička and Domalski's work, the values have been extracted from a more recent article published in 2005 by M. Zábranský and V. Růžička [17] which states that its values are more versatile and accurate.

Table 7: Isosorbide constituent groups for Růžička and Zábranský method

Group	N_k	a_j	b_j	d_j
		Isosorbide		
O-(H)(C)	2	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281
O-(C)$_2$	2	6.35342	-0.969836	-0.0378285
THF rsc	2	-0.975198	-2.13999	0.633211

Note that in this method it is also considered the effect of the chemical ring structures by adding a ring strain contribution (rsc) correction. The values for the other compounds are included in Appendix 3.

Parameters A, B and D calculated by equations 26-28 are shown in Table 8.

Table 8: Parameters A, B and D obtained by equations 26-28

Compound	A	B	D
Sorbitol	79.389	-59.536	17.610
1,4-sorbitan	52.457	-38.770	12.503
3,6-sorbitan	52.457	-38.770	12.503
Isosorbide	25.524	-18.003	7.396
1,5-sorbitan	18.883	-14.146	8.060
2,5-sorbitan	52.457	-38.770	12.503

A simplification of equation 25 has been made and equation 29 will be considered instead:

$$C_{pL} = a + bT + dT^2 \tag{29}$$

where a, b, and d are:

$$a = R \cdot A \tag{30}$$

$$b = \frac{R \cdot B}{100} \tag{31}$$

$$d = \frac{R \cdot D}{100^2} \tag{32}$$

After applying equation 29 for each compound, the following expressions are obtained:

$$C_{pL_{Sorbitol}} = 660.081 - 4.950T + 1.46 \cdot 10^{-2}T^2 \tag{33}$$

$$C_{pL_{1,4-sorbitan}} = 436.150 - 3.223T + 1.04 \cdot 10^{-2}T^2 \tag{34}$$

$$C_{pL_{3,6-sorbitan}} = 436.150 - 3.223T + 1.04 \cdot 10^{-2}T^2 \tag{35}$$

$$C_{pL_{Isosorbide}} = 212.218 - 1.497T + 6.15 \cdot 10^{-3}T^2 \tag{36}$$

$$C_{pL_{1,5-sorbitan}} = 156.999 - 1.176T + 6.70 \cdot 10^{-3}T^2 \tag{37}$$

$$C_{pL_{2,5-sorbitan}} = 436.150 - 3.223T + 1.04 \cdot 10^{-2}T^2 \tag{38}$$

$$C_{pL_{H_2O}} = 96.106 - 0.126T - 1.92 \cdot 10^{-4}T^2 \tag{39}$$

All heat capacities have been calculated by using Růžička and Zábranský method except for water, whose expression has been extracted from the Chemical Engineering Research

Information Center [18]. Although the original equation was a third-degree polynomial it has been rearranged into a second-degree polynomial to simplify the equation.

4.5. **COMPARISON BETWEEN THE METHODS**

Despite the contribution methods developed in the previous sections, a series of other methods were previously considered but then discarded either due to its complexity or a lack of applicability.

As mentioned previously, the liquid heat capacities were firstly determined by tabulated values from an article from Růžička and Domalski [16], but then a more recent article from M. Zábranský and V. Růžička introduced new tabulated values [17]. The difference between the heat capacities calculated with the two versions are significant; for example, the value of the heat capacity of sorbitol at 200 K calculated with the first version is 283.81 J/(mol·K) and with the second version equals 255.75 J/(mol·K). Since Zabránský and Růžička state in their article that their values should be more accurate and versatile than the previous ones, only the newer version has been considered.

It was also considered using Anderson-Beyer-Watson's contribution method [19] to determine the entropy because this method avoids the calculation of the symmetry correction, which is very complex for the molecules involved in the reactions. However, the method was not applicable to all the compounds due to some structural conformations that could not be estimated such as the tetrahydrofuran and tetrahydropyran rings.

In the case of the enthalpy of formation, since their values had to be estimated in the liquid phase, Domalski and Hearing's method was considered immediately. Furthermore, the combination between Joback and Vetere's method was also considered. In addition, M. Vasiliu et al. used a computational chemistry method named G3MP2 in 2011 to predict the thermodynamic properties of some compounds [20]. This computational method will be considered to compare the values obtained (Table 9).

Table 9: Enthalpies of formation in the liquid phase at standard conditions using Domalski and Hearing method, the combination of Joback and Vetere methods, and the G3MP2 computational method

	$\Delta_f H_{lliquid}$ [kJ/mol]		
Compound	Domalski and Hearing	Joback and Vetere	G3MP2
Sorbitol	-1331.00	-1372.97	-1281.14
1,4-sorbitan	-1041.13	-1096.26	-995.37
3,6-sorbitan	-1041.13	-1096.26	-
Isosorbide	-751.26	-753.14	-738.48
1,5-sorbitan	-1057.51	-1115.04	-
2,5-sorbitan	-1041.13	-1107.68	-1009.18

Comparing the values, the difference is not that much, especially in the case of isosorbide. However, these enthalpies cannot be compared with experimental values because at the present time there is yet no scientific article reporting those experimental values. Therefore, the criteria to select the values to then use in the estimation of the equilibrium constant has been the following: The combination of two methods (Joback and Vetere) probably leads to a larger error than using one method. On the other hand, Domalski and Hearing method do not differentiate between the carbon atoms that form a molecular ring. That is the reason why in Domalski and Hearing method, 2,5-sorbitan has the same enthalpy of formation as 1,4-sorbitan and 3,6-sorbitan. Thus, since it is not possible to know which method leads to a major deviation, Joback and Vetere method has been chosen to calculate the equilibrium constant because 2,5-sorbitan should not have the exact same enthalpy of formation as other sorbitans.

Also notice that all the properties of both 1,4-sorbitan and 3,6-sorbitan are exactly the same. That is because none of the contribution methods used in the work consider the spatial layout of the atoms distributed in the molecules.

It was also considered to determine the enthalpy of formation in the solid phase, and then by summing the enthalpy of fusion obtain it in the liquid phase. Two methods were used; one developed by A. Salmon et al. [21] and the other developed by N. Cohen [22]. Nevertheless, the methods have not been included in the work, even though it is fundamental to acknowledge the existence of this possibility to determine the enthalpy of formation in the liquid phase.

5. DETERMINATION OF THE EQUILIBRIUM CONSTANT

As there is too much uncertainty on the calculation of the symmetry correction factor (S_S^o) and its value has a substantial influence on the equilibrium constant, two procedures will be considered to estimate the equilibrium constant:

(1)   In the first one the term S_S^o will have the same values as in Table 2.
(2)   In the second procedure, the S_S^o term will be ignored instead.

Thus, the importance of the symmetry entropy contribution will be reflected in the results.

Table 10 shows the parameters that will be used to estimate the equilibrium constant. Procedure 1 is indicated with (1) and procedure 2 with (2).

Table 10: Enthalpies and entropies of formation at standard state conditions in the liquid phase considered to calculate the equilibrium constant

Compound	$\Delta_f H°$ [kJ/mol]	$\Delta_f S°$ [J/(mol·K)] (1)	$\Delta_f S°$ [J/(mol·K)] (2)
Sorbitol	-1372.97[a]	228.34[b]	209.20[b]
1,4-sorbitan	-1096.26[a]	218.43[b]	195.38[b]
3,6-sorbitan	-1096.26[a]	218.43[b]	195.38[b]
Isosorbide	-753.14[a]	200.70[b]	181.56[b]
1,5-sorbitan	-1115.04[a]	206.31[b]	183.26[b]
2,5-sorbitan	-1107.68[a]	207.89[b]	195.38[b]
H_2O	-285.8[c]	69.95[c]	69.95[c]

(a) Values determined by Joback and Vetere methods.

(b) Values determined by method of Domalski and Hearing.

(c) Values taken from NIST [14].

Once the enthalpies and entropies of formation of each parameter have been determined, the enthalpy and entropy of every reaction must be calculated using the equations 10 and 11. Table 11 shows the values obtained.

Table 11: Enthalpies and entropies of all reactions at standard state conditions in the liquid phase

Reaction	$\Delta_r H°$ [kJ/mol]	$\Delta_r S°$ [J/(mol·K)] (1)	$\Delta_r S°$ [J/(mol·K)] (2)
R_1	-27.91	53.68	47.92
R_2	-9.14	65.80	60.04
R_3	-9.14	65.80	60.04
R_4	-20.56	49.49	49.49
R_5	57.32	57.99	52.22
R_6	57.32	57.99	52.22

Note that first dehydration reactions (R_1, R_2, R_3 and R_4) are exothermic while the second dehydration reactions (R_5 and R_6) are endothermic. The enthalpies of reaction have a great dependence on the method used to estimate the properties of the compounds, since a little difference of the properties could easily switch the negative values into positive and vice versa. Reactions 2 and 3 could be treated as a single reaction since the entropies and enthalpies of reaction are equal, and same for reactions 5 and 6. Nonetheless, the reactions will be treated separately to emphasize the fact that it is an estimation that has been effectuated by using some contribution methods which are not completely accurate.

In section 6 the enthalpies of reaction are compared to those calculated in the G3MP2 computational method [20] and to those estimated in a recent article [23].

Also notice that in the second procedure (2) all the entropies except for R_1 are equal. Not only is this because 1,4-sorbitan 3,6-sorbitan and 2,5-sorbitan have the same entropy of formation, but also because the difference between the entropy of formation of sorbitol and those sorbitans is the same as the difference of entropy of formation between isosorbide and the sorbitans (equations 40 and 41).

$$\Delta S_f^o {}_{(1,4-sorbitan)} = \Delta S_f^o {}_{(3,6-sorbitan)} = \Delta S_f^o {}_{(2,5-sorbitan)} \qquad (40)$$

$$\Delta S_f^o {}_{(sorbitol)} - \Delta S_f^o {}_{(1,4-sorbitan)} = \Delta S_f^o {}_{(1,4-sorbitan)} - \Delta S_f^o {}_{(isosorbide)} \quad (41)$$

Since the reaction takes place at relatively high temperatures, the values in Table 11 must be converted to the correct temperature by using Kirchhoff equations (equations 12 and 13). Since the main purpose is to find an expression of the equilibrium constant in dependance of the temperature, the heat capacities must be integrated as a temperature function (equations 33-39).

After doing so, the expressions can be simplified as:

$$\Delta_r H(T) = \alpha + \beta T + \gamma T^2 + \delta T^3 \qquad (42)$$

$$\Delta_r S(T) = A + B\ln(T) + \Gamma T + \Delta T^2 \qquad (43)$$

where α, β, γ, and δ are the values obtained after simplifying the enthalpy of reaction at any temperature. And same for A, B, Γ and Δ but for the entropy of reaction at any temperature.

By substituting them in equation 7 the equilibrium constant for every i reaction is:

$$\ln(K_i) = -\frac{\alpha_i + \beta_i T + \gamma_i T^2 + \delta_i T^3}{R\,T} + \frac{A_i + B_i\ln(T) + \Gamma_i T + \Delta_i T^2}{R} \qquad (44)$$

If K is isolated:

$$K_i = EXP\left(\frac{-\frac{\alpha_i}{T} - \beta_i - \gamma_i T - \delta_i T^2 + A_i + B_i\ln(T) + \Gamma_i T + \Delta_i T^2}{R}\right) \qquad (45)$$

where R equals 8.314472 J/(mol·K) and T needs to be in Kelvin. Parameters α, β, γ, δ, A, B, Γ, and Δ for each reaction i are indicated in tables 12 and 13.

Table 12: Parameters α, β, γ and δ used to estimate the equilibrium constant

Reaction	α	β	γ	δ
R_1	3151.19	-406.98	1.82	$-2.71 \cdot 10^{-3}$
R_2	-2948.08	-127.83	0.80	$-1.48 \cdot 10^{-3}$
R_3	-2948.08	-127.83	0.80	$-1.48 \cdot 10^{-3}$
R_4	-14366.16	-127.83	0.80	$-1.48 \cdot 10^{-3}$
R_5	63512.14	-127.83	0.80	$-1.48 \cdot 10^{-3}$
R_6	63512.14	-127.83	0.80	$-1.48 \cdot 10^{-3}$

Table 13: Parameters A, B, Γ, and Δ used to estimate the equilibrium constant

Reaction	A (1)	A (2)	B	Γ	Δ
R_1	1640.65	1636.74	-406.98	3.65	$-4.07 \cdot 10^{-3}$
R_2	508.46	504.56	-127.83	1.60	$-2.22 \cdot 10^{-3}$
R_3	508.46	504.56	-127.83	1.60	$-2.22 \cdot 10^{-3}$
R_4	497.92	504.56	-127.83	1.60	$-2.22 \cdot 10^{-3}$
R_5	500.65	504.56	-127.83	1.60	$-2.22 \cdot 10^{-3}$
R_6	500.65	504.56	-127.83	1.60	$-2.22 \cdot 10^{-3}$

Notice that the only parameter that differs from the first to the second procedure is A.

In order to examine the behaviour of the reactions, the equilibrium constant has been calculated at different temperatures ranging 180 - 200 °C for both procedures (Table 14-15).

Table 14: Values of the equilibrium constants of all reactions at 180-200 ˚C for procedure (1)

First procedure (1) ($S_S^o \neq 0$)						
T (˚C)	K_1	K_2	K_3	K_4	K_5	K_6
180	$1.60 \cdot 10^5$	$5.55 \cdot 10^3$	$5.55 \cdot 10^3$	$3.23 \cdot 10^4$	$4.74 \cdot 10^{-5}$	$4.74 \cdot 10^{-5}$
185	$1.34 \cdot 10^5$	$5.02 \cdot 10^3$	$5.02 \cdot 10^3$	$2.83 \cdot 10^4$	$5.19 \cdot 10^{-5}$	$5.19 \cdot 10^{-5}$
190	$1.13 \cdot 10^5$	$4.52 \cdot 10^3$	$4.52 \cdot 10^3$	$2.47 \cdot 10^4$	$5.64 \cdot 10^{-5}$	$5.64 \cdot 10^{-5}$
195	$9.42 \cdot 10^4$	$4.06 \cdot 10^3$	$4.06 \cdot 10^3$	$2.15 \cdot 10^4$	$6.10 \cdot 10^{-5}$	$6.10 \cdot 10^{-5}$
200	$7.85 \cdot 10^4$	$3.65 \cdot 10^3$	$3.65 \cdot 10^3$	$1.87 \cdot 10^4$	$6.56 \cdot 10^{-5}$	$6.56 \cdot 10^{-5}$

Table 15: Values of the equilibrium constants of all reactions at 180-200 ˚C for procedure (2)

Second procedure (2) ($S_S^o = 0$)						
T (˚C)	K_1	K_2	K_3	K_4	K_5	K_6
180	$1.00 \cdot 10^5$	$3.47 \cdot 10^3$	$3.47 \cdot 10^3$	$7.18 \cdot 10^4$	$7.58 \cdot 10^{-5}$	$7.58 \cdot 10^{-5}$
185	$8.40 \cdot 10^4$	$3.13 \cdot 10^3$	$3.13 \cdot 10^3$	$6.28 \cdot 10^4$	$8.30 \cdot 10^{-5}$	$8.30 \cdot 10^{-5}$
190	$7.04 \cdot 10^4$	$2.83 \cdot 10^3$	$2.83 \cdot 10^3$	$5.48 \cdot 10^4$	$9.03 \cdot 10^{-5}$	$9.03 \cdot 10^{-5}$
195	$5.89 \cdot 10^4$	$2.54 \cdot 10^3$	$2.54 \cdot 10^3$	$4.77 \cdot 10^4$	$9.76 \cdot 10^{-5}$	$9.76 \cdot 10^{-5}$
200	$4.91 \cdot 10^4$	$2.28 \cdot 10^3$	$2.28 \cdot 10^3$	$4.15 \cdot 10^4$	$1.05 \cdot 10^{-4}$	$1.05 \cdot 10^{-4}$

As a reminder, the temperatures to calculate the equilibrium constants at a certain temperature, must be in Kelvin units.

Notice that in both cases, the equilibrium constant of the first dehydration reactions (R_1, R_2, R_3 and R_4) is greater than the unit ($K > 1$). This means that the equilibrium is shifted towards the products rather than the reactants, which is favourable. However, in the case of the second dehydration reactions (R_5 and R_6), the equilibrium constant is lower than the unit ($K < 1$) which means that the equilibrium is shifted towards the reactants.

The fact that reactions 1 to 4 are exothermic implies that K_1, K_2, K_3 and K_4 gradually decrease when the temperature increase. Contrarily, as R_5 and R_6 are endothermic, K_5 and K_6 increase when the temperature is risen.

Furthermore, K_1 K_2 and K_3 of the first procedure at any temperature are 60% greater than their respective equilibrium constants for procedure 2. However, K_4 (2) is more than twice the value of K_4 (1), and K_{5-6} (2) are 60% greater than K_{5-6} (1). This is a significant representation of the importance on how the properties are estimated, especially the S_S^o factor.

6. RESULTS AND DISCUSSIONS

A very recent article developed by Lei Wang et al. was published during the develop of this work [23]. Hence, a comparison of some of the results obtained in both studies as well as in the G3MP2 computational [20] work will be conducted in this section.

Lei Wang et al. studied the thermodynamic calculations and reaction kinetics of the sorbitol dehydration to isosorbide catalyzed by $NbOPO_4$. It is noteworthy that in their work, the molecular structure of 1,4-sorbitol and 3,6-sorbitan are considered to have an extra alcohol (-OH) bonded to the tetrahydrofuran ring (Figure 9).

1,4-Sorbitan   3,6-Sorbitan
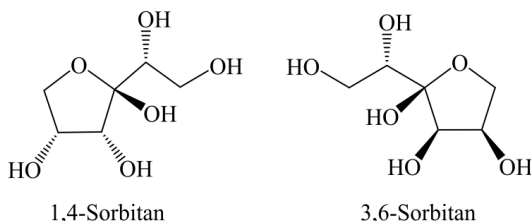
Figure 9: Molecular structure of 1,4-sorbitan and 3,6-sorbitan considered in Lei Wang et al. work. Image extracted from Lei Wang et al. work. [23]

Firstly, the enthalpies of some reactions are given at different temperatures. In Lei Wang et al. study the enthalpies of reaction of the first (R_{2-3}) and second dehydration (R_{5-6}) are given at 473.15 K (Table 16). In the case of the G3MP2 computational work they are given at 298.15 K (Table 17).

Table 16: Comparison between enthalpies of reactions at 473.15 K of different studies

Study	$\Delta_r H°_{(R2-3)}$ [kJ/mol]	$\Delta_r H°_{(R5-6)}$ [kJ/mol]
Lei Wang et al. [23]	25.31	47.09
Present work	-41.00	25.46

Table 17: Comparison between enthalpies of reactions at 298.15 K of different studies

Study	$\Delta_r H°_{(R2\text{-}3)}$ [kJ/mol]	$\Delta_r H°_{(R5\text{-}6)}$ [kJ/mol]
G3MP2 [20]	-23.43	-28.87
Present work	-9.14	57.32

The first thing to notice is that in the computational study the values of the enhalpies are both negative (exothermic) whereas in Lei Wang et al. work they are both positive (endothermic). Even though the values are not given at the same temperature it is clear that there is a discrepancy between the studies on how the reactions behave. The values obtained in the present work also differ from both studies, as the first dehydration reactions have resulted to be exothermic, while endothermic for the second dehydration reactions. This is probably due to the inaccuracy of the methods employed and in the case of Lei Wang et al. work probably due to the extra alcohol considered in 1,4-sorbitan and 3,6-sorbitan.

Lei Wang et al. also estimated the equilibrium constant of the two dehydration reactions (R$_{2\text{-}3}$ and R$_{5\text{-}6}$). Table 18 compares the values obtained in that study at 473.15 K with the ones calculated in the present work at the same temperature.

Table 18: Comparison between equilibrium constants at 473.15 K of different studies

Study	$K_{2\text{-}3}$	$K_{5\text{-}6}$
Lei Wang et al. [23]	$4.06 \cdot 10^7$	5.32
Present work	$3.65 \cdot 10^3$	$6.56 \cdot 10^{-5}$

As it is observed, in the present work both equilibrium constants are more than 10^4 times smaller than the ones in the other study, which is probably due to the discrepancy between enthalpies of reaction. Moreover, unlike the present work, K_2 in the other study is greater than 1 which means that the equilibrium is shifted towards the products.

Although in the computational work the equilibrium constants are not calculated, an approximation has been made considering the enthalpies of reaction mentioned in Table 17. The values of the equilibrium constant at 298.15 K are shown in Table 19.

Table 19: Comparison between equilibrium constants at 298.15 K of different studies

Study	K_{2-3}	K_{5-6}
G3MP2 [20]	$1.75 \cdot 10^7$	$6.15 \cdot 10^7$
Present work	$5.46 \cdot 10^4$	$4.85 \cdot 10^{-8}$

The first thing to note is that the equilibrium constant of the second dehydration is completely different. That is because unlike the present work, the enthalpy of the second dehydration reaction in the computational work is exothermic.

Furthermore, the order of magnitude of K_{2-3} obtained in the present work is 3 times lower than K_{2-3} in the G3MP2 computational method. Additionally, as in both works the first dehydration reaction is determined to be exothermic, the tendency of the equilibrium constant is to decrease when the temperature is risen.

7. CONCLUSIONS AND FURTHER WORK

Taking into account all the results obtained and the comparison with other non-experimental works, it is clear that there is a great discordance on the thermodynamical estimation of the reaction network which occur in the dehydration of sorbitol to isosorbide. One explanation could be that some of the estimation methods are not exact, especially when applied to complex molecules like the ones studied.

Not only some methods might be inaccurate, but also lacking in some experimental values like the ring strain correction of tetrahydropyran in Domalski and Hearing's method. In addition, the entropy of symmetry (S_s^o) has brought a lot of uncertainty to the entropy estimation mainly because of the complexity of the procedure and the inherent intricacies of molecular symmetry, that reach beyond my area of expertise.

Upcoming studies should focus on, first, developing a more intelligible method to determine the symmetry entropy of complex molecules, and second and more important, obtaining the equilibrium constant experimentally. This would lead to a better understanding of the thermodynamics of the reaction path of sorbitol to isosorbide.

It is fundamental to have an accurate comprehension of the behaviour of the reactions to:

- Enable the correct design of the reactors in which the reactions would take place.
- Determine the optimal reaction conditions (temperature, pressure, initial relation between reactants, etc.).
- Catalyst selection.

In conclusion, there is still a lot of research to be done to implement the reaction on an industrial scale. Moreover, it is of great importance to be aware of the environmental problem that humanity is facing nowadays, otherwise it will not be possible to successfully substitute the petrol-based plastics for bioplastics.

ACRONYMS

a	Activity
T_b	Boiling temperature [K]
T_c	Critical temperature [K]
P_c	Critical pressure [bar]
$\Delta_f H^o$	Enthalpy change of formation [kJ/mol]
$\Delta_f S^o$	Entropy changes of formation [J/(mol·K)]
$\Delta_r H^o$	Enthalpy change of reaction [kJ/mol]
$\Delta_r S^o$	Entropy changes of reaction [J/(mol·K)]
$\Delta_v H^o$	Enthalpy of vaporization [kJ/mol]
K	Equilibrium constant
ΔG^o	Gibbs free energy [kJ/mol]
C_{pL}	Liquid heat capacity [J/(mol·K)]
R	Gas constant (8.314472 J/(mol·K))
η	Number of structural isomers
σ	Number of indistinguishable conformations
r	Reaction rate
k	Reaction rate constant
ν	Stoichiometric coefficient
S_s^o	Symmetry entropy
THF	Tetrahydrofuran
THP	Tetrahydropyran

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APPENDICES

APPENDIX 1: DOMALSKI AND HEARING METHOD

In the following tables, Domalski and Hearing method values of the thermodynamic parameters of every group conforming each molecule are shown. In this method, the possible rings present in the molecules are considered by adding a ring strain contribution that is then summed to the global enthalpy and entropy of the molecules. *THF rsc* stands for the ring strain contribution of a tetrahydrofuran ring and *THP rsc* for a tetrahydropyran ring.

As mentioned in section 4, the value of the THP rsc of the entropy in the liquid phase is unknown. Since these values have a great impact on the global entropy, it has been considered to make an approximation of the value rather than considered it null. The approximation has been done using the known values of the THP rsc in the gas phase and the THF rsc in both gas and liquid phase (equation 46):

$$THP \; rsc \; _{Liquid} = THP \; rsc \; _{Gas} \frac{THF \; rsc \; _{Liquid}}{THF \; rsc \; _{Gas}} \tag{46}$$

Table 20: Sorbitol constituent groups for Domalski and Hearing method

Sorbitol			
Group	N_k	$\Delta_f H°$ [kJ/mol]	$S°$ [J/mol·K]
O-(H)(C)	6	-191.5	43.89
C-(H)$_2$(C)(O)	2	-35.8	32.59
C-(H)(C)$_2$(O)	4	-27.6	-29.83

Table 21: 1,4-sorbitan constituent groups for Domalski and Hearing method

1,4-sorbitan			
Group	N_k	$\Delta_f H°$ [kJ/mol]	$S°$ [J/mol·K]
O-(H)(C)	4	-191.5	43.89
C-(H)$_2$(C)(O)	2	-35.8	32.59
C-(H)(C)$_2$(O)	4	-27.6	-29.83
O-(C)$_2$	1	-110.83	26.78
THF rsc	1	17.7	47.18

Table 22: 3,6-sorbitan constituent groups for Domalski and Hearing method

3,6-sorbitan			
Group	N_k	$\Delta_f H°$ [kJ/mol]	$S°$ [J/mol·K]
O-(H)(C)	4	-191.5	43.89
C-(H)$_2$(C)(O)	2	-35.8	32.59
C-(H)(C)$_2$(O)	4	-27.6	-29.83
O-(C)$_2$	1	-110.83	26.78
THF rsc	1	17.7	47.18

Table 23: 1,5-sorbitan constituent groups for Domalski and Hearing method

1,5-sorbitan			
Group	N_k	$\Delta_f H°$ [kJ/mol]	$S°$ [J/mol·K]
O-(H)(C)	4	-191.5	43.89
C-(H)$_2$(C)(O)	2	-35.8	32.59
C-(H)(C)$_2$(O)	4	-27.6	-29.83
O-(C)$_2$	1	-110.83	26.78
THP rsc	1	1.32	35.06[a]

(a) Approximate value using equation 46.

Table 24: 2,5-sorbitan constituent groups for Domalski and Hearing method

2,5-sorbitan			
Group	N_k	$\Delta_f H°$ [kJ/mol]	$S°$ [J/mol·K]
O-(H)(C)	4	-191.5	43.89
C-(H)$_2$(C)(O)	2	-35.8	32.59
C-(H)(C)$_2$(O)	4	-27.6	-29.83
O-(C)$_2$	1	-110.83	26.78
THF rsc	1	17.7	47.18

APPENDIX 2: JOBACK METHOD

The following tables show the contribution values of each group used in Joback method. The nomenclature is different from other methods as in Joback method the values for the atoms that are forming a ring are considered and specified with a (ss) for non-aromatic rings and (ds) for aromatic rings. However, the method does not differentiate the type of atoms that are bonded except for the hydrogens. The number in parenthesis next to each group is the number of atoms that are bonded (excluding hydrogens).

Table 25: Sorbitol constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		Sorbitol			
OH (1)	6	-208.04	92.88	0.0741	0.0112
CH$_2$ (2)	2	-20.64	22.88	0.0189	0
CH (3)	4	29.89	21.74	0.0164	0.002

Table 26: 1,4-sorbitan constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		1,4-sorbitan			
OH (1)	4	-208.04	92.88	0.0741	0.0112
CH$_2$ (2)	1	-20.64	22.88	0.0189	0
CH (3)	1	29.89	21.74	0.0164	0.002
O(ss) (2)	1	-138.16	31.22	0.0098	0.0048
CH$_2$(ss) (2)	1	-26.80	27.15	0.01	0.0025
CH(ss) (3)	3	8.67	21.78	0.0122	0.0004

Table 27: 3,6-sorbitan constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		3,6-sorbitan			
OH (1)	4	-208.04	92.88	0.0741	0.0112
CH$_2$ (2)	1	-20.64	22.88	0.0189	0
CH (3)	1	29.89	21.74	0.0164	0.002
O(ss) (2)	1	-138.16	31.22	0.0098	0.0048
CH$_2$(ss) (2)	1	-26.80	27.15	0.01	0.0025
CH(ss) (3)	3	8.67	21.78	0.0122	0.0004

Table 28: 1,5-sorbitan constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		1,5-sorbitan			
OH (1)	4	-208.04	92.88	0.0741	0.0112
CH$_2$ (2)	1	-20.64	22.88	0.0189	0
O(ss) (2)	1	-138.16	31.22	0.0098	0.0048
CH$_2$(ss) (2)	1	-26.80	27.15	0.01	0.0025
CH(ss) (3)	4	8.67	21.78	0.0122	0.0004

Table 29: 2,5-sorbitan constituent group contribution values for Joback method

Group	N_k	hfk [kJ/mol]	tbk [K]	tck [K]	pck [bar]
		2,5-sorbitan			
OH (1)	4	-208.04	92.88	0.0741	0.0112
CH$_2$ (2)	2	-20.64	22.88	0.0189	0
O(ss) (2)	1	-138.16	31.22	0.0098	0.0048
CH(ss) (3)	4	8.67	21.78	0.0122	0.0004

APPENDIX 3: RŮŽIČKA AND ZÁBRANSKÝ METHOD

The following tables show the tabulated values of each group for Růžička and Zábranský method, which have been extracted from their own article in 2004 [17]. As mentioned in section 4.4 Růžička and Zábranský improved the method made by Růžička himself and Domalski.

Table 30: Sorbitol constituent groups for Růžička and Zábranský method

Sorbitol				
Group	N_k	a_i	b_i	d_i
O-(H)(C)	6	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281

Table 31: 1,4-sorbitan constituent groups for Růžička and Zábranský method

1,4-sorbitan				
Group	N_k	a_i	b_i	d_i
O-(H)(C)	4	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281
O-(C)$_2$	1	6.35342	-0.969836	-0.0378285
THF rsc	1	-0.975198	-2.13999	0.633211

Table 32: 3,6-sorbitan constituent groups for Růžička and Zábranský method

3,6-sorbitan				
Group	N_k	a_i	b_i	d_i
O-(H)(C)	4	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281
O-(C)$_2$	1	6.35342	-0.969836	-0.0378285
THF rsc	1	-0.975198	-2.13999	0.633211

Table 33: 1,5-sorbitan constituent groups for Růžička and Zábranský method

1,5-sorbitan				
Group	N_k	a_i	b_i	d_i
O-(H)(C)	4	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281
O-(C)$_2$	1	6.35342	-0.969836	-0.0378285
THP rsc	1	-34.549	22.4833	-3.81053

Table 34: 2,5-sorbitan constituent groups for Růžička and Zábranský method

2,5-sorbitan				
Group	N_k	a_i	b_i	d_i
O-(H)(C)	4	16.156	-11.938	2.8512
C-(H)$_2$(C)(O)	2	0.517007	1.2663	-0.0940
C-(H)(C)$_2$(O)	4	-4.64439	2.3899	0.17281
O-(C)$_2$	1	6.35342	-0.969836	-0.0378285
THF rsc	1	-0.975198	-2.13999	0.633211