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Functional Properties of Sugar Alcohols as Low-Calorie Sugar Substitutes

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INTRODUCTION

In recent years, low-calorie or reduced-calorie foods have generated a great deal of interest not only by consumers and the food industry but also by nutritionists and clinicians. As a result, a large number of sugars, sugar derivatives, and alternative sweeteners have been studied to evaluate their suitability as sugar substitutes for products oriented to consumers who must, or desire to, control their total caloric intake, who are diabetic, or who prefer noncalorigenic food products.

Sugar alcohols, also widely referred to as polyols, have become primary alternatives not only because of their low caloric nature, but also because they have other desirable technical and related characteristics. For example, sugar alcohols have low reactivity when heated, resulting in reduced caramelization, act as humectants, and provide desirable mouth-feel. Similarly, the sugar alcohols are useful alternatives to sucrose in confections because they provide desirable taste but lessen the potential risks for dental caries.

What are sugar alcohols?

Strictly speaking, "sugar alcohols" and "polyols" are not synonymous, although the terms are frequently used interchangeably in the literature. Technically, sugar alcohols constitute a subset of polyols. Polyols are defined as monomeric, dimeric, or oligomeric polyhydroxy alcohols or reduced derivatives of mono-, di-, and oligosaccharides. On the other hand, sugar alcohols are polyhydroxy alcohols, resulting from the reduction of the aldehyde or ketone functional groups from sugars. However, those will be used in this paper as having the same meaning, as the terminology is not a point of discussion and will not be an issue on a practical basis.

For better understanding, various and well known sugar alcohols are shown here, in order of molecular size, with the indication of corresponding sugars.

Table 1. Varieties of sugar alcohols

	No of Carbons	Sugars	Sugar alcohols
Monomeric	3		Glycerol
	4		Erythritol
	5	Xylose	Xylitol
	6	Glucose	Sorbitol
		Fructose	Mannitol
Di- and Oligomeric	12	Maltose	Maltitol
	12	Isomaltulose	Isomalt
	12	Lactose	Lactitol
		Corn Syrup (Glucose)	Hydrogenated Starch Hydrolysate

How are they made available?

Sugar alcohols are distinguished from other saccharides by the reduction of the aldehyde or ketone functions. Some polyols(sugar alcohols) are present in nature, particularly in the vegetable kingdom, but as their extraction is not a commercially viable approach, generally, they are manufactured on an industrial scale by catalytic hydrogenation of saccharides.

Industrial production of sugar alcohols is explained in a simplified scheme here. As shown, sorbitol, maltitol and hydrogenated starch hydrolysate are derived from corn, potato or other starches by way of hydrogenation of corn syrup, glucose or maltose. Likewise, mannitol, isomalt or partly glucose are produced from sugar cane or sugar beat through hydrogenation of fructose, isomaltulose or glucose. Lactitol is produced by hydrogenation of lactose from milk whey and xylitol is produced by hydrogenation

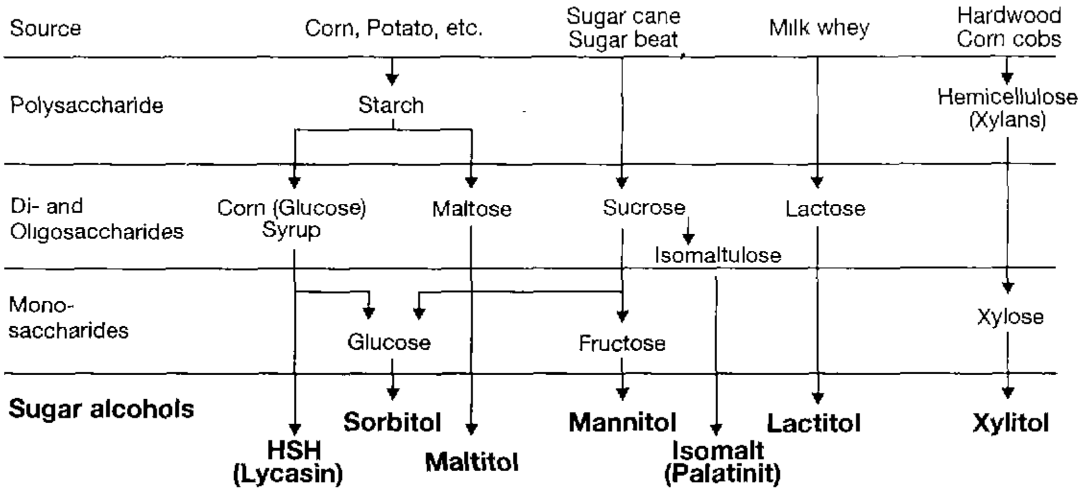


Fig. 1. Industrial production of sugar alcohols.

of xylose from xylans as hemicellulose contained in hardwood or corn cobs.

In another point of view, the chemical structure of sugar alcohols and their manufacturing process enable their classification as:

(1) Manufactured by fermentation: Erythritol
(2) Hydrogenated monosaccharides: Xylitol, Sorbitol, Mannitol
(3) Hydrogenated disaccharides: Maltitol, Isomalt(Palatinit), Lactitol
(4) A mixture of hydrogenated saccharides and polysaccharides: Hydrogenated glucose syrup or hydrogenated starch hydrolysate(HSH)

Why are they used?

The substitution in a sugar of an alcohol function instead of an aldehyde or ketone group transforms a cyclical form into a linear form, and has its consequences on sweetness and/or taste profiles, physical and chemical properties, and further physiological functionalities. The consequences on physico-chemical properties are expressed particularly in higher chemical stability, higher affinity for water, lower capacity to crystallization and reduction of the Maillard reaction. Another consequence, but of greater importance to us is the physiological functionality of lower caloric contribution within human metabolism.

Sweetness and taste profiles of sugar alcohols

Relative sweetness of various sugar alcohols compared with that of sucrose is illustrated. As shown here, although the sweetness varies in each sugar alcohol, they could be summarized in several groups, such as xylitol being equivalent to sucrose, erythritol and maltitol being approximately 80% sweet, sorbitol and mannitol being about a half, and among those sugar alcohols isomalt and lactitol are the least sweet at approximately one third of sucrose. It is interesting that most sugar alcohols have negative heat of solution which is also expressed as cooling effect and those effects are rather stronger than that of sucrose. As shown in the graph, they can be considered practically in two groups, in order of the effects, erythritol, xylitol, mannitol and sorbitol are much stronger than

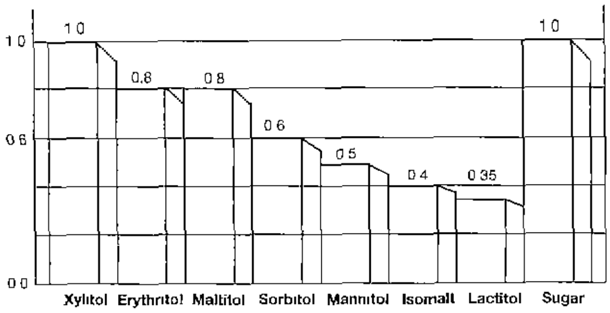


Fig. 2. Relative sweetness of sugar alcohols.

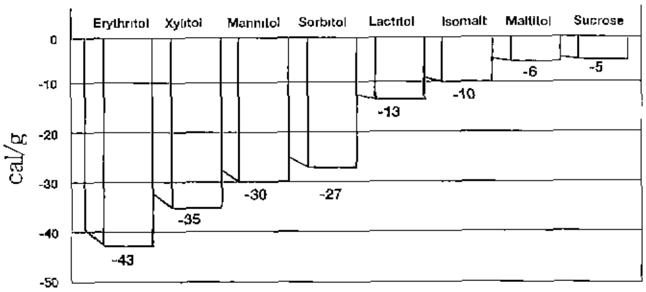


Fig. 3. Cooling effect of sugar alcohols.

sucrose and lactitol, isomalt and maltitol are in weaker group having closer cooling effect to sucrose.

In addition to those relative sweetness and cooling effects, the sweet taste profiles such as onset of sweetness, duration of action, and etc. are also quite important factors for selecting one or more of them for substituting sucrose in food formulations. The decision should be made by taking such taste characteristics as relative sweetness, cooling effects and other taste profiles into consideration depending on the purpose of use or concept of new foods under development.

Physical and chemical properties of sugar alcohols

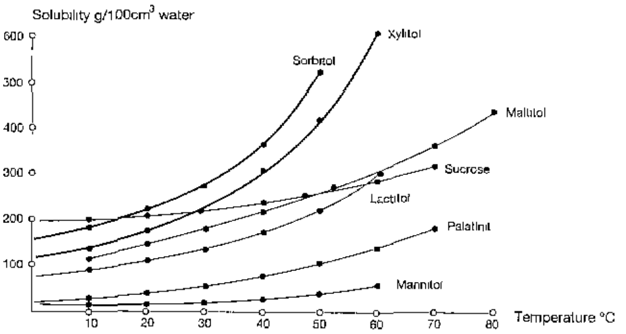
Here are some physical and chemical properties of sugar alcohols shown. With regard to the solubility in water, it varies greatly depending on sugar alcohols, but it could be considered in three groups:

(1) More soluble than sucrose-Sorbitol, Xylitol
(2) Almost equal-Maltitol, Lactitol
(3) Less soluble than sucrose-Erythritol, Isomalt, Mannitol

Hygroscopicity is also important to evaluate sugar alcohols. It characterizes the capacity of a product to retain or absorb water. It varies depending on the form of materials, such as in a solution or crystalline form, and further it depends on a condition of relative humidity. Nevertheless, if we could classify their hygroscopicity on a practical understanding basis, erythritol, mannitol, lactitol and isomalt are in lower hygroscopic group and xylitol, sorbitol and maltitol are in relatively higher group.

Table 2. Physical and chemical properties of sugar alcohols

Sugar alcohol	M.W.	Solubility g/100g H_2O at 20℃	Hygroscopicity	Maillard reaction
Erythritol	122	50	Low	No
Xylitol	152	170	High(>Su)	No
Sorbitol	182	220	High(>Ma)	No
Mannitol	182	17	Low	No
Lactitol	344	170	Low	No
Maltitol	346	150	High(>Xy)	No
Isomalt	360	25	Low	No
Sucrose	342	195	–	Yes



(from *'Le Bot'*, 1983)

Fig. 4. Solubility of sugar alcohols.

Physiological functionalities of sugar alcohols

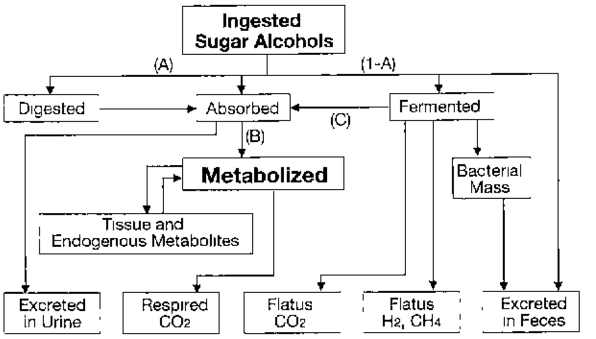
Regarding physiological functionalities of sugar alcohols, there are three major field of interests to be considered.

(1) Non/Anti-cariogenic properties-for reduction in risks or prevention of dental caries
(2) No insulin required-for diabetic patients to consume without or with minimum increase in insulin response
(3) Non/Low caloric-for low or reduced calorie foods having equivalent tastes or even better mouth-feel in certain specific food applications

Due to limitation in this paper, the discussion will focus on the caloric utilization issues on sugar alcohols.

What are the caloric utilization factors of sugar alcohols?

Traditional classification has differentiated simply between high intense, noncaloric sweeteners such as aspartame and caloric bulk sweeteners such as sugar substitutes. Until recently, a caloric value of about 4kcal/g has been ascribed to bulk sweeteners which include sugar alcohols, such as sorbitol, xylitol, isomalt, lactitol and maltitol. The validity of the postulated value of 4kcal/g was questioned for the first time about 25 years ago, when it was found by Japanese investigators that maltitol was poorly absorbed from the intestinal tract of rats. Since then, it has become clear from a number of animal experiments and human studies that sugar alcohols are indeed not absorbed completely but that bacterial fermentation in the gut makes the not-absorbed portion, at least in part, metabolically available to the host because the fermentation end-product are efficiently absorbed and utilized. Such caloric utilization factors have been studied and calculated by numerous researchers all over the world, and presently the specific caloric value(s) are designated or accepted by the EC Commission in Europe, by the



(Modified from '*Bär*', 1990)

Fig. 5. Metabolic and caloric utilization of sugar alcohols.

Ministry of Health and Welfare in Japan and by the FDA in the United States.

To better understand the caloric utilization factors of sugar alcohols, here is a simplified metabolic diagram for ingested sugar alcohols.

When a sugar alcohol is ingested, generally only certain portion of the ingested material is absorbed in the small intestine directly or through digestion (A) and the remaining portion (1-A) goes to the large intestine without degradation, digestion or absorption. (A) portion absorbed is not necessarily completely utilized as caloric, as in the diagram some may be excreted in urine without caloric contribution. Therefore, (B) will be the really calorically utilizable fraction. Likewise, some of (1-A) portion is excreted in feces without metabolic contribution. Only (C) portion of (1-A) through fermentation by intestinal bacteria will be available for caloric utilization.

Dutch Government(Nutrition Council, 1987)

In the Netherlands, and Expert Group, the Committee on Polyols under the Nutrition Council submitted its report on the available calorie of sugar alcohols to the Dutch government in 1987. The Committee considered the so-called "multi-factorial method" of estimating available calorie as superior to other "experimental methods" such as direct and indirect calorimetory. Further, the evaluation by the Committee included chemical description of the sugar alcohols, the digestion and absorption in the small intestines, the microbiologic breakdown of unabsorbed carbohydrates in the colon, and utilization of the resulting products such as acetic, propionic and butyric acids.

Based on the report from the Nutrition Council, the Dutch government proposed the following formula to estimate the caloric values for each sugar alcohols. Factors A, B and C were estimated and used based on the available factorial data and assumptions.

Table 3. Estimates of caloric values by Dutch government (Nutrition Council, 1987)

$E=[(A\times B)+(1-A)\times C]\times 16.5/4.2\times R(\fallingdotseq 1)$

Sugar Alcohol	A	B	C	E (kcal/g)
Xylitol	0.75	1.00	0.5	3.54
Sorbitol	0.50	1.00	0.5	2.99
Mannitol	0.25	0.50	0.5	1.99
Maltitol	0.40	1.00	0.5	2.84
Isomalt	0.20	(1.0+0.5)/2	0.5	2.23
Lactitol	0	0	0.5	2.03

A: Fraction of ingested material absorbed in the small intestine
B: Fraction of material utlized after absorption in the small intestine
C: Portion of energy available from fermentation in the large intestine
R: Relative heat of combustion of material compared with sucrose(≒1)

European Economic Community Council Directive(90/496/EEC)

As you may know, the European Economic Community Council issued a directive in 1990, declaring that caloric values for sugar alcohols should be a unitary figure of 10kj/g or 2.4kcal/g for all sugar alcohols.

This decision was based on recognition of differences between calorie from sugars and sugar alcohols and, in part, on the reconsideration of the conclusion of the Dutch Nutrition Council in 1987, that pointed out that, despite the need for labeling purposes, it was not possible to calculate precise caloric values for each sugar alcohols.

When the EEC Council adopted the unitary number of 2.4kcal/g, they explained that, taking into account the widely recognized 20% imprecision of metabolizable calorie measurement, the caloric values of sugar alcohols currently

Table 4. Estimates of caloric values by European Economic Community Council Directive(90/496/EEC)

The energy value to be declared shall be calculated using the following conversion factors:

-Carbohydrate(except polyols)	4kcal/g-17kJ/g
-Polyols	2.4kcal/g-10kJ/g
-Protein	4kcal/g-17kJ/g
-Fat	9kcal/g-37kJ/g
-Alcohol(ethanol)	7kcal/g-29kJ/g
-Organic acid	3kcal/g-13kJ/g

used by EC at 2.4 plus or minus 20% which means 1.9 to 2.9, accommodates the caloric values of most sugar alcohols estimated by the factorial methods. For the purpose of nutrition labeling, the rounded value of 2.4 appropriate.

Fermentation equations/Bio-available energy

As explained earlier, unabsorbed portion of ingested sugar alcohols, referred to as (1-A), are, through fermentation in the colon, partially utilized as caloric sources. There are several studies reported in the literature of the fermentation equations on animals and on human subjects. Here, as examples, are the suggested equations based on the study using bovine rumen by Hungate in 1966 and human colon by Miller and Wolin in 1979.

Table 5. Fermentation equations

1 Bovine Rumen(Hungate, 1966)

$$57.5C_6H_{12}O_6 \longrightarrow 65\text{Acetate}+20\text{Propionate}+15\text{Butyrate}+60CO_2+35CH_4+25H_2O$$

$$57.5\times180(\text{g}) \longrightarrow 65\times209+20\times365+15\times522(\text{kcal})$$

$$1\text{g} \longrightarrow 2.77\text{kcal}$$

2. Human Colon(Miller and Wolin, 1979)

$$34.5C_6H_{12}O_6 \longrightarrow 48\text{Acetate}+11\text{Propionate}+5\text{Butyrate}+23.75CO_2+34.25CH_4+10.5H_2O$$

$$34.5\times180(\text{g}) \longrightarrow 48\times209+11\times365+5\times522(\text{kcal})$$

$$1\text{g} \longrightarrow 2.68\text{kcal}$$

1g $C_6H_{12}O_6$ provides approx. 2.7kcal as gross energy

As seen in the suggested equations and the calculation of theoretical gross energy production through fermentation, both equations indicate that 1g of hexose($C_6H_{12}O_6$) provides only 2.7kcal in stead of 4kcal/g as gross or combustion energy, if it goes through fermentation in the colon. However, this 2.7kcal/g should not be fully bioavailable. For example, as it is well recognized that the available energy or caloric value of acetic acid for labeling purposes is agreed as 2.4kcal/g. It indicates that only 70% (2.40/3.48=0.69) of gross energy is biologically available in the colon, when the substance is fermented by the intestinal bacteria. As a result, 70% of 2.7kcal/g should be the net energy of fermented substance. This number of 1.89 could be referred to as rounded factor of 0.5 of (C) in the Dutch formula.

Bio-Available Energy

1. 1g $C_6H_{12}O_6$ provides 2.7kcal
2. Approx. 70% bio-available

Combustion E. → Available E.

Acetate: 3.48kcal/g → 2.40kcal/g

3. Fecal loss(e.g. 15% for Maltitol)

$$1\text{g Sugar Alcohol} \longrightarrow 2.7\times0.7\times0.85=1.6\text{kcal}$$

Japanese MHW

In Japan, newly established Nutrition Labeling Standards have been enacted in May 1996. For the purpose of labeling caloric content of foods, the caloric values for specifically poorly digested or absorbed carbohydrates, such as sugar alcohols and oligosaccharides required to be determined. MHW applied rather "multi-factorial methods in combination with manufacturers; in-house information" than experimental or analytical methods which once MHW have adopted. After reviewing available data, taking into account the status in Europe and in the US, finally the caloric values were determined by rounding off the study results in 0, 1, 2, 3 and 4.

Table 6. Estimates of caloric values by Japanese MHW

	Results(kcal/g)	Caloric Value(kcal/g)
Erythritol	0~0.3	0
Mannitol	2.1	2
Maltitol	1.6	
Lactitol	1.6	
Isomalt	1.6	
Oligosaccharides	1.6~2.2	
Sorbitol	2.8~3.0	3
Xylitol	2.4~3.6	
Oligosaccharides	3.0~3.4	
Others	4	4

US FDA

Previously, the United States Code of Federal Regulations had indicated that all carbohydrates have a uniform value of 4kcal/g for labeling purposes. Regulations promulgated as a result of the Nutrition Labeling and Education Act of 1990 have been incorporated in the 1993 Code of Federal Regulations, 21 CFR 101.9. In part, these changes indicated that in addition to using general factors of 4, 4 and 9 calories per gram for protein, carbohydrate and fat, caloric content may be calculated by "using data for specific food factors for particular foods or ingredients approved by the FDA or by other means, as appropriate; …".

Under such circumstances, the members of the Calorie Control Council(CCC)'s Polyol Committee requested that the Life Science Research Office(LSRO), Federation of American Societies for Experimental Biology(FASEB) provide an objective assessment of the scientific information available on certain sugar alcohols and prepare a

Table 7. Estimates of caloric values by US FDA-1993 Code of federal regulations(21 CFR 101.9)

(A) Using specific Atwater factors(i.e., the Atwater method) given in Table 13, "Energy Value of Foods--Basis and Derivation," by A.L. Merrill, and B. K. Watt, United States Department of Agriculture(USDA) Handbook No.74(slightly revised, 1973), …;

(B) Using the general factors of 4, 4, and 9 calories per gram for protein, total carbohydrate, and total fat, respectively, as described in USDA Handbook No.74(slightly revised 1973) pp.9-11, …;

(C) Using the general factors of 4, 4, and 9 calories per gram for protein, total carbohydrate less the amount of insoluble dietary fiber, and total fat, respectively, as described in USDA Handbook No.74(slightly revised 1973) pp.9-11, …;

(D) Using data for specific food factors for particular foods or ingredients approved by the Food and Drug Administration(FDA) and provided in parts 172 or 184 of this chapter, or by other means, as appropriate; or

(E) Using bomb calorimetry data and subtracting 1.25 calories per gram protein to correct for incomplete digestibility, as described in USDA Handbook No.74(slightly revised 1973) p.10,….

Table 8. LSRO/FASEB reviews of data estimating caloric values of sugar alcohols(1994)

Reference	Isomalt	Lactitol	HSH	Maltitol	Mannitol	Sorbitol	Xylitol	Comments
Dwivedi, 1977				3.6				Maltitol based on Rennhard and Bianchine, 1976
					2.0			Mannitol based on Nasrallah and Iber, 1969
Den Uyl, 1987		≦2.0						Multiple data sources used
Nutrition Council, 1987	2.4	2.0	2.9	2.9	1.9	3.0	3.6	Net energy without water of crystalization
Ziesenitz and Siebert, 1987	2.0	2.0		2.4	<4.0	4.0	<4.0	Values from multiple data sources
Bassler, 1989	2.0	2.0		2.0 and 2.9		3.0		Two values for maltitol based on fasting vs non-fasting subjects; Proposed arithmetic mean for mixture
Bar, 1990		2.28		3.26		2.6		Values based on a factorial calculation model
Bemier and Pascal, 1990	2.4~2.9			2.8~3.2	1.5	2.0~2.6		Fasting subjects
	≦3.0			3.5		3.3~3.9		Subjects with meals
		1.4-2.5	3.2				3.3~3.9	Multiple data sources included
Livesey, 1990a	≦2.0							Based on *in vivo* animal studies
Livesey, 1990b	1.5							Based mainly on Van Weerden et al, 1991 a,b
Oku, 1990				1.3~2.4				Based on multiple data sources
Bar, 1991							2.8~2.9	Calculated value from multiple data sources
Comite European des Fabricants de Sucre, 1991	2.6	2.0	3.2	3.2	1.5	3.2	3.2	Mean values from Nutrition Council, 1987, and Fabricants de Sucre, 1991
Dwivedi, 1991					2.0	3.		Mannitol based on Nasrallah and Iber, 1969
Moskowitz, 1991			4.0					No specific supporting references
Oku, 1991				1.8				Calculated vlaue from rat studies
Strater and Irwin, 1991	2.0							Based on data from multiple sources
Bar, 1992a	2.4	2.4		2.4	2.4	2.4	2.4	Recommended unitary value with range of 1.9~2.9
Livesey, 1992	2.0~2.9	1.7~2.0		3.7	<2.0	>2.0<3.7	>3.0	Based on multiple data sources
Seniko, 1992	1.5~2.0							Cited multiple studies
LSRO Expert Panel(1994)	~2.0	1.6~2.2	2.8~3.2	2.8~3.2	1.6	1.8~3.3	~2.4	

report on the energy available from them.

After a thorough review of the available data over a two year period, the Expert Panel reached the conclusions indicated in the Table 8.

Caloric Utilization Factors of Sugar Alcohols

In summary, those caloric values adopted or suggested in EC, Japan and US are here. Reviewing those carefully, although there are certain differences in precise numbers, generally, they seem to be in a certain agreeable range on a practical food labeling purposes.

Table 9. Summary in kcal/g of sugar alcohols

	Dutch	EC	Japan	LSRO/FASEB
Erythritol	–	2.4	0	–
Xylitol	3.5	2.4	3	~2.4
Sorbitol	3.0	2.4	3	1.8~3.3
Mannitol	2.0	2.4	2	1.6
Lactitol	2.0	2.4	2	1.6~2.2
Maltitol	2.8	2.4	2	2.8~3.2
Isomalt	2.2	2.4	2	~2.0

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5. The Evaluation of the Energy of Certain Sugar Alcohols used as Food Ingredients by LSRO, FASEB(1994)
6. Nutrition Improvement Law Last Amended in 1995 and Subsequent Ministerial Ordinances and Notifications in 1996 and 1997