Nutrafoods (2024) 1 551 - 559 DOI 10.17470 NF-024-0064 Schweitzer

Original Research

Replacing sugar with the polyol isomalt: technological advances and nutritional benefits focusing on blood glucose management

Abstract

National and international authorities and organizations, including the WHO, recommend limiting dietary consumption of added sugars. Isomalt is a well-established polyol used in food manufacturing to replace sugars. It is the only sugar-free bulk sweetener exclusively made from pure beet sugar. Due to its physical and technological properties, such as a mild, sugar-like taste and low hygroscopicity, it is an ideal sugar substitute for many foods such as confectionery or dry and soft baked goods. Furthermore, isomalt provides several nutritional benefits, including low digestibility, very low glycaemic and insulinaemic response and low physiological energy value (approximately 8.4 kJ/g). It is also non-cariogenic. This review gives an overview of the technological properties of isomalt and the latest advances in food applications. It also discusses the physiological health benefits of isomalt, with an emphasis on its low glycaemic and insulinaemic effects. These benefits have now been corroborated with a series of randomized controlled trials conducted according to international standards in blood glucose response testing for a variety of food applications. Our study confirms a reduced postprandial glycaemic and insulin response of various confectionary products in which sugar was replaced by isomalt. These findings agree with previous data and extend our knowledge by providing evidence for various sweets containing isomalt. Isomalt, with its technological advantages and nutritional benefits, is a proven versatile sugar substitute for supporting a sugar-reduced diet that combines health and indulgence at the same time.

Lisa Schweitzer[1*]

Rudy Wouters[2]

Stephan Theis[1]

[1] BENEO Institute, c/o BENEO GmbH, Wormser Straße 11, 67283 Obrigheim, Germany

[2] BENEO Technology Center, c/o BENEO GmbH, Aandorenstraat 1, 3300 Tienen, Belgium

*Corresponding author
Lisa Schweitzer

Email: lisa.schweitzer@beneo.com
Tel.: +49 6359 803831

Keywords: Isomalt, polyol, sugar substitute, glycaemia, insulin, sweeteners

Introduction

The increase in diet-related health challenges in society and its economic impacts have led to a strong public health interest in reducing the intake of dietary sugar [1-4]. National and international authorities and organizations recommend limiting the consumption of added sugars from different food products [4,5]. For example, the WHO recommends limiting the intake of free sugars to less than 10% of total energy intake (strong recommendation), and suggests a further reduction below 5% of total energy intake (conditional recommendation) [4].

Consequently, there is growing interest in products with reduced sugar content, prompting food research for alternatives that offer improved health benefits in addition to high sensory and technological qualities.

Polyols, like isomalt, are low-digestible carbohydrates used as a bulk sweetener. They are used in the food industry to replace sugars like sucrose or glucose syrup [6]. Isomalt is derived from a natural source and is the only bulk sweetener made from pure beet sugar by two steps: the enzymatic rearrangement of sucrose into isomaltulose, followed by the catalytic hydrogenation of isomaltulose into isomalt. Chemically, it is a mixture of the polyols 1-O-*α*-D-glucopyranosyl-D-mannitol (GPM) and 6-O-*α*-D-glucopyranosyl-D-sorbitol (GPS) [7].

In terms of application, isomalt has a very similar organoleptic and technological profile to sugar. It is odourless, crystalline and low-hygroscopic, exhibiting a lower hygroscopicity compared with the majority of polyols, and significantly lower than sugar [8]. Its negligible moisture absorption, even at relatively high levels of humidity, has advantages in applications such as candies, mints and coated food products. As isomalt possesses a minimal cooling effect similar to sucrose, it can be used to develop formulations with a very natural taste profile [9]. Furthermore, its mild sweetness facilitates enhanced flavour release in delicate and subtle fruit flavours [10] and its low solubility contributes to improved flavour retention [7,11]. These technological and sensory properties render isomalt a valuable sugar substitute in the food industry, offering an opportunity to create naturally sourced (re)formulations.

Isomalt also offers several widely acknowledged physiological health benefits, including low digestibility and a non-cariogenic nature [6,9,12]. As a result of the incomplete hydrolysis in the human small intestine, isomalt is low-calorie, delivering only half the physiological energy value of sugar (approximately 8·4 kJ/g) [13,14]. Furthermore, owing to the strong bond in GPS and GPM, the hydrolysis of isomalt takes approximately eleven times longer than sucrose, resulting in a very low effect on blood glucose and insulin levels [15–19]. These properties position isomalt as an ideal sugar substitute from a nutritional perspective, allowing for the replacement of sugar, without compromising health or taste.

This review highlights the technological properties of isomalt and discusses recent advances in food applications. It also reviews available literature on the physiological benefits of isomalt with an emphasis on its low glycaemic and insulinaemic characteristics. In addition, the paper extends on existing knowledge by providing recent data from randomized controlled trials using state-of-the-art methodology to investigate the impact of isomalt on blood glucose and insulin response in various sweets.

Technological aspects and recent advances in food applications

Next to traditional major bulk sweeteners such as sugar, glucose and glucose/fructose syrups, the use of polyols is well established in 'no added sugar', 'sugar-free', 'tooth-friendly' and 'calorie reduced' confectionery and baked goods. Polyols provide bulk, texture, body and a mouthfeel similar to sucrose but at a reduced sweetness for most polyols except xylitol.

Sensorial properties

The sweetness profile of isomalt is a pure and clean sweetness without any aftertaste. It therefore fits very well with many intense sweeteners. The sweetening power of isomalt is between 0.45 and 0.6 compared with sucrose (=1.0). Isomalt is often combined with high intensity sweeteners or with other polyols because of its synergistic sweetening effects. Sensorial evaluations show that such combinations can match the sweetness and taste profile of sugar. An additional benefit of these combinations is that isomalt shows an ability to mask aftertastes from these high intensity sweeteners [20].

A lot of polyols have a negative heat of solution, resulting in a cooling effect in the mouth, which is not always a desired characteristic in baked goods or chocolate applications. However, the cooling effect of isomalt is limited and close to that of sugar.

Applications: Hard candies

Isomalt is commonly used in the food industry to produce hard candies and other confectionery products. It has become popular as an alternative to traditional sugars like sucrose due to its unique technical properties. In addition to its sugar-like sweetness profile, it provides a sweet taste without the bitterness or aftertaste sometimes associated with other sugar substitutes like stevia or aspartame. When used in hard candy production, it allows for a smooth and stable process during boiling and cooling, resulting in a consistent candy texture.

Isomalt has low hygroscopic properties, meaning it does not readily absorb moisture. This is beneficial for hard candies because it helps to maintain transparency, prevent unwanted stickiness and extend shelf-life. A water content below 2% is key to this [20]. When producing hard candies, some important characteristics of isomalt need to be considered such as the lower solubility, a higher boiling point and a lower viscosity of the melt. However, no significant process adaptations are required.

Isomalt has excellent clarity when melted and hardened, making it ideal for creating visually appealing hard candies with a clear or glass-like appearance. This clarity allows confectioners to embed objects like flowers or designs within the candy.

Isomalt can be easily moulded into various shapes and designs; confectioners often use it to make decorative elements for cakes and pastries and for sculpting artistic showpieces and displays.

Chewing gum

Isomalt is commonly used in chewing gum as a sugar substitute and bulking agent. An important characteristic is the low solubility of isomalt, which allows isomalt to remain in crystalline form in the chewing gum mass. This results in a better product stability and less hardening of the centre during shelf-life. Chewing gum manufacturers often use isomalt in combination with other sugar alcohols for this reason.

Chewing gum is composed of several ingredients. The gum base is a critical component – a mixture of elastomers, resins, waxes and fillers that give the gum its chewy texture and ability to hold flavour. As the gum is chewed, mechanical forces and moisture in the mouth gradually break down the encapsulation and release the flavour. Isomalt crystals show a porous surface that absorbs a significant amount of flavour. The flavour is released slowly because of the low solubility of isomalt, leading to longer-lasting flavour in chewing gum compared with other sweeteners [20].

Coating is another notable area where isomalt's low solubility and improved tendency to crystallize is of particular benefit. In this application, Isomalt GS is recommended, resulting in a good crunch, bright colours and excellent shelf-life. Crystallized isomalt is transparent, leading to perfectly coloured bright coatings. Isomalt also has the advantage of setting quickly once cooled; this allows for efficient and consistent pan-coating as it reduces the time needed for the coated products to dry and harden.

Baked goods

The use of isomalt as a partial or complete sugar substitute is advantageous in several types of baked goods. Isomalt exhibits similar behaviours to sugar in its effect on starch gelatinization and dough rheology [21]. Isomalt ST is the preferred choice for hard-baked goods such as biscuits. Due to its higher solubility, Isomalt GS works excellently in soft-baked goods such as muffins and cakes.

Chocolate

Isomalt LM is a special isomalt grade with a lower moisture content specifically developed for chocolate applications. Isomalt LM allows for regular chocolate process to be used without significant adaptations, resulting in a 'sugar-free' or 'no added sugar' chocolate with excellent snap, texture and taste. A slightly higher amount of fat needs to be added before mixing and refining due to the specific surface of the isomalt particle. The use of Isomalt LM allows the manufacturer to apply the same conching temperature used for regular sugar formulations. Because of the lower sweetness of isomalt, combinations with intense sweeteners are often used. However, the lower sweetness can also help to intensify the cacao flavours.

Another benefit is that there is no cooling effect, which is undesirable for chocolate. The snap of chocolate is an important sensorial characteristic. Typically, sugar-free chocolate based on polyols is slightly softer than regular sugar-based versions. A structure build-back ingredient such as isomalt can rebuild the regular sugar-like snap and texture. Isomalt can be used as sole sugar replacer or in combination with other sweeteners such as maltitol for this technological reason.

Health potential of isomalt

Review of the low glycaemic and insulinaemic properties

Numerous scientific studies have demonstrated the very low effect isomalt has on postprandial blood glucose and insulin levels [6,15,17,18]. In 2011, the low glycaemic property of isomalt as a sugar replacer was also recognized by the European Food Safety Authority (EFSA) as having a beneficial physiological effect. This was followed by the approval of a health claim by the European Commission, i.e. "Consumption of foods/drinks containing isomalt instead of sugar induces a lower blood glucose rise after their consumption compared to sugar-containing foods/drinks" [22]. The beneficial physiological effect of isomalt as a sugar substitute can be attributed to a slower and incomplete digestion in the small intestine, which was previously demonstrated in individuals with ileostomy [14], resulting in a low physiological energy value of approximately 8.4 kJ/g [13]. Accordingly, when compared with sucrose and other rapidly digestible carbohydrates, isomalt prevents hyper- and hypoglycaemia, which is accompanied by a negligible rise in insulin [18]. The majority of studies in this area investigated the effects on glucose metabolism following administration of pure isomalt compared with pure high glycaemic index (GI) carbohydrates like sucrose [16,18]. Gee *et al*. provided data on an isomalt-based milk chocolate [17]. This study, involving six males with diabetes, confirmed the effectiveness of isomalt when incorporated into foods: postprandial blood glucose response was reduced by 36% compared with conventional milk chocolate containing sucrose ($iAUC_{5h}$, $p<0.05$). This result was supported by a lower insulin secretion. The determination of the relative blood glucose response of isomalt compared with the reference glucose revealed an approximate GI of 9 [6], making it suitable for both healthy individuals and individuals with diabetes.

Beyond the postprandial response, Holub *et al*. (2009) conducted a 12-week human intervention study in individuals with type 2 diabetes and examined the effects of a diet with sweets containing 30 g/d isomalt instead of sugar on parameters of metabolic control [23] . While the intervention diet was well-tolerated, it resulted in improved parameters of glucose homeostasis, e.g. HbA1c, fasting blood glucose or insulin when compared with the control diet. The study therefore showed that when compared with high GI sweeteners, a continuous diet containing isomalt significantly improved glucose homeostasis in individuals with type 2 diabetes [23]. The study is in accordance with a meta-analysis by Livesey *et al*. (2008) that demonstrated that the consumption of a low GI diet compared with a high GI diet resulted in improved health markers of longer-term glycaemic control, such as fasting blood glucose, glycated proteins or insulin resistance [24].

Together, these studies support the importance of a low GI diet in reducing the risk of developing cardiometabolic diseases like type 2 diabetes while highlighting the health potential of using isomalt as a sugar substitute to maintain glucose homeostasis [24,25].

A series of randomized controlled trials replacing sugar with isomalt in sweets

Sweet snacks in particular often contain high amounts of sugar and consequently result in a steep and rapid increase in blood glucose accompanied by a high insulin secretion [26]. Despite this physiologically unfavourable characteristic and the urgent call from the authorities like WHO or EFSA to reduce the daily intake of dietary sugars [4,5], consumers still crave sweet foods. Replacing the sugar in sweets with low glycaemic carbohydrates is a powerful approach as it would satisfy the craving of the consumer and contribute to maintaining a normal blood glucose response, thereby reducing the risk of adverse health outcomes [27,28].

With this in mind, we conducted a series of randomized controlled trials to investigate the effects of four different sweets on postprandial blood glucose and insulin response. The studies were conducted according to the guidelines laid down in the Declaration of Helsinki. Written informed consent was obtained from all participants. The sweets were chocolate, candies, mints and jam, each containing 25 g sugar (i.e. conventional sweets) or 25 g isomalt (i.e. isomalt sweets). Products were comparable in appearance, taste, and sweetness.

For each trial, 10 healthy adults (mean age: 40.6 ± 7.0 years, BMI: 23.5 ± 3.2 kg/m²) were recruited. Participants consumed realistic portion sizes of the sweets in a randomized order in the morning after an overnight fast. Capillary blood samples were taken at baseline up to 180 minutes postprandial. Blood glucose was determined by the glucose oxidase technique, insulin was determined using an electro-chemiluminescence immunoassay.

The resulting data shows that replacing sugar with isomalt led to a significantly lower postprandial blood glucose response for all sweet products **(Table 1, Fig 1)**. The two-hour iAUC ($iAUC_{2h}$) ranged from 332.3 to 652.5 mg/dL*min and 683.8 to 1441.4 mg/dL*min for isomalt sweets and conventional sweets. Isomalt therefore reduced the $iAUC_{2h}$ by 71%, 69%, 61% and 5% in mints, jam, candies and chocolate respectively ($p<0.05$ for mints, jam and candies). In addition, isomalt prevented the steep increase in glucose levels, which was characterized by a 46% to 83% lower incremental glucose peak (iCmax: all *p*<0.05). Additionally, a repeated measures (ANOVA) for variance analysis of blood glucose response showed a significant intervention effect for the test sweets – jam, candies and mints (all *p*<0.05, data not shown). For jam and chocolate, there was a significant time effect (all *p*<0.05, data not shown), even though the time* intervention interaction was not significant.

The lower glycaemic response seen with isomalt was accompanied by lower insulin levels **(Table 1, Figure 1)**. Accordingly, insulin peak (iCmax) was significantly reduced by 92%, 89%, 72% and 70% for candies, mints, chocolate and jam respectively when sugar was replaced by isomalt (all *p*<0.05, **Table 1**). In addition to the lower insulin increase, the 2-h incremental insulinaemic response ($iAUC_{2h}$) was significantly reduced by 87%, 76%, 60% and 58% following the isomalt compared with the sugar variants of candies, mints, jam and chocolate respectively (all *p*<0.05). Carrying out a repeated measures ANOVA on insulin levels revealed a significant intervention effect for all tested sweets (*p*<0.05, data not shown). A significant effect of time was seen for jam, and a significant time* intervention interaction for both, jam and candies (*p*<0.05, data not shown).

Pooling the blood glucose as well as insulin data from all sweets showed an overall remarkable advantage to consuming sweets containing isomalt compared with conventional, sugar-sweetened products for the respective parameters **(Fig. 1)**.

Table 1: Postprandial glycaemic and insulinaemic response to isomalt sweets vs conventional sweets[a]

		Blood glucose parameters		**Insulin parameters**	
		iCmax (mg/dL)	**$iAUC_{2h}$ (mgdL/*min)**	**iCmax (μU/mL)**	**$iAUC_{2h}$ (μU/mL)**
Jam	SUC	43.9 ±16.1	1297.6 ± 437.8	23.1 ± 13.7	752.0 ± 410.0
	ISO	8.4 ± 6.6	396.1 ± 566.0	6.9 ± 5.1	300.5 ± 154.2
	ΔISO-SUC	***-35.6 ± 19.6****	**-901.6 ± 797.5***	***-16.2 ± 14.8****	**-451.5 ± 459.9***
Candies	SUC	47.8 ± 20.8	1441.4 ± 773.7	31.2 ± 10.9	1019.1 ± 464.0
	ISO	8.6 ± 8.1	567.4 ± 683.4	2.6 ± 2.3	129.9 ± 131.5
	ΔISO-SUC	***-39.2 ± 20.2****	**-874.1 ± 813.4***	***-28.6 ± 10.2****	**-889.2 ± 459.4****
Mints	SUC	37.4 ± 13.0	1159.0 ± 602.2	22.4 ± 12.9	752.8 ± 468.0
	ISO	6.5 ± 3.8	332.3 ± 266.1	2.5 ± 3.3	177.8 ± 206.0
	ΔISO-SUC	***-30.9 ± 12.5****	**-826.7 ± 684.6***	***-19.9 ± 15.1****	**-575.0 ± 611.5***
Chocolate	SUC	20.0 ± 5.9	683.8 ± 270.1	22.5 ± 10.4	835.2 ± 415.2
	ISO	10.9 ± 7.4	652.5 ± 516.6	6.2 ± 4.2	354.2 ± 244.2
	ΔISO-SUC	***-9.2 ± 10.4****	-31.4 ± 604.6	***-16.3 ± 9.1****	**-481.0 ±403.1***

[a]Data presented as mean ± SD. Significant differences between test foods are presented in bold and were assessed using paired t- test:***p*<0.001, **p*<0.05.

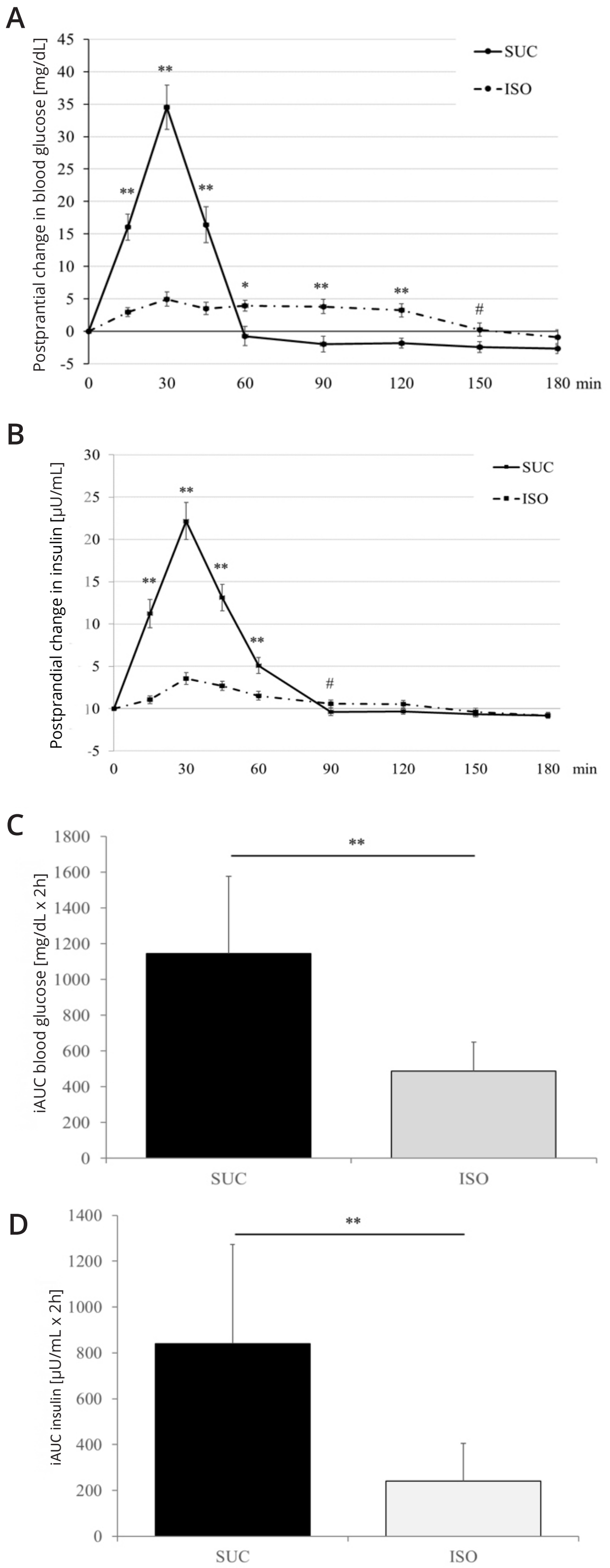

Figure 1: Pooled data of the postprandial blood glucose response (A,C) and insulin response (B,D) after consumption of test foods (i.e. candies, mints, jam and chocolate) containing 25g isomalt (– –▲– –) vs 25 g sucrose (——■——). iAUC = incremental area under the curve; ISO = isomalt; SUC = sucrose; panel A,B: mean ± SEM, panel C,D: mean ± SD; differences in glucose response at individual time points and iAUC between ISO and SUC sweets were tested using paired t-test: ***p*<0.001, **p*<0.05, #*p*<0.1.

Conclusions

National and international authorities, including the WHO, strongly recommend reducing the dietary intake of added sugar, prompting food industry research on sugar substitutes in foods. Isomalt, a well-established polyol and the only sugar replacer made from pure beet sugar, is used as a bulk sweetener, replacing sugar 1:1. It possesses unique technical properties such as a sweetness profile similar to sucrose with about 45% to 65% sweetness, no aftertaste, a minimal cooling effect or low hygroscopicity. These properties make it a suitable sugar replacement in a variety of food applications such as confectionery or baked goods.

In addition to its technological benefits, isomalt has been shown to have negligible effects on glycaemia and insulinaemia, making it a promising ingredient for both consumers seeking a healthier diet and for individuals with diabetes. The current study presents findings from a series of randomized controlled trials conducted according to international standards in blood glucose testing and provides data that extends on existing knowledge for isomalt-based products. Accordingly, the replacement of sugar by isomalt in jam, candies, mints and chocolate resulted in a marked reduction of postprandial glycaemic and insulinaemic response. There is also evidence to suggest that the continuous replacement of sugar with isomalt could result in a decreased risk of obesity, type 2 diabetes, and cardiovascular disease by improving various risk markers [23]. However, further long-term studies are warranted.

In conclusion, isomalt represents a valuable sugar substitute for the food industry to produce high-quality, high-sensory food applications while maintaining blood glucose homeostasis and avoiding hyperglycaemic events.

For that reason, the incorporation of isomalt as a naturally sourced sugar replacer is an effective strategy for reducing sugar intake in the diet and is a promising ingredient to support national and international recommendations.

Conflict of interest

The authors are employees of BENEO/ Südzucker Group.

References

1. Geneva: World Health Organization (2018) Non communicable diseases country profiles 2018. Available from: https://www.who.int/docs/default-source/ncds/9789241514620 (Accessed: 22/10/2023)

2. Bommer C, Sagalova V, Heesemann E, Manne-Goehler J, Atun R, Bärnighausen T, Davies J, Vollmer S (2018) Global economic burden of diabetes in adults: Projections from 2015 to 2030. Diabetes Care 41(5):963–970

3. Bloom DE, Cafiero ET, Jané-Llopis E, Abrahams-Gessel S, Bloom LR, Fathima S (2011) The global economic burden of non-communicable diseases. World Economic Forum. Available from: https://www.weforum.org/publications/global-economic-burden-non-communicable-diseases/ (Accessed: 22/10/2023)

4. World Health Organization (2015) Guideline: Sugars intake for adults and children. Available from: https://www.who.int/publications/i/item/9789241549028 (Accessed: 22/10/2023)

5. Turck D, Bohn T, Castenmiller J, Henauw S de, Hirsch-Ernst KI, Knutsen HK, et al. (2022) Tolerable upper intake level for dietary sugars. EFSA Journal 20(2):e07074

6. Livesey G (2003) Health potential of polyols as sugar replacers, with emphasis on low glycaemic properties. Nutr Res Rev 16(2):163–191

7. Schiweck H (1980) Palatinit® - Herstellung, technologische Eigenschaften und Analytik palatinithaltiger Lebensmittel [Palatinit® - Production, technological properties and analysis of Palatinit-containing foods]. Alimenta 19:5–16

8. Weisser H, Weber J, Locin M (1982) Water vapor sorption isotherms of sugar substitutes in the temperature range 25 to 80°C. ZFL 33(2):89–97

9. Sentko A, Bernard J (2012) Isomalt. In: O'Brien A (ed), Alternative sweeteners, 4th edn. CRC Press, Boca Raton, pp 275–297

10. Paulus K, Fricker A (1980) Zuckerersatzstoffe - Anforderungen und Eigenschaften am Beispiel von Palatinit [Sugar substitutes - requirements and properties using the example of Palatinit]. Z Lebensmitteltechnologie Und Verfahrenstechnik 31(3):128–132

11. Bollinger H (1987) Palatinit® (Isomalt) - ein kalorienreduzierter Zuckeraustauschstoff - Technologische und physiologische Eigenschaften [Palatinit® (Isomalt) - a low-caloric sugar substitute - Technological and physiological properties]. Gordian 87(5):92–95

12. Gehring F, Karle EJ (1981) [Sweetening agent, Palatinit under specific consideration as to microbiological and caries-prophylactic aspects]. Z Ernahrungswiss 20:96–106

13. Livesey G, Buss D, Coussement P, Edwards D, Howlett J, Jonas D, Kleiner J, Müller D, Sentko A (2000) Suitability of traditional energy values for novel foods and food ingredients. Food Control 11(4):249–289

14. Langkilde AM, Andersson H, Schweizer TF, Würsch P (1994) Digestion and absorption of sorbitol, maltitol and isomalt from the small bowel. A study in ileostomy subjects. Eur J Clin Nutr 48(11):768–775

15. Grupp U, Siebert G (1978) Metabolism of hydrogenated palatinose, an equimolar mixture of α-D-Glucopyranosido-1,6-sorbitol and α-D-Glucopyranosido-1,6-mannitol. Res Exp Med (Berl) 173(3):261–278

16. Petzoldt R, Laurer P, Spengler M, Schoffling K (1982) [Palatinite in type II diabetics. Effect on blood-glucose, serum-insulin, C-peptide and free fatty acids]. Dtsch Med Wochenschr 107:1910–1913

17. Gee JM, Cooke D, Gorick S, Wortley GM, Greenwood RH, Zumbe A, Johnson IT (1991) Effects of conventional sucrose-based, fructose-based and isomalt-based chocolates on postprandial metabolism in non-insulin-dependent diabetics. Eur J Clin Nutr 45(11):561–566

18. Thiébaud D, Jacot E, Schmitz H, Spengler M, Felber JP (1984) Comparative study of isomalt and sucrose by means of continuous indirect calorimetry. Metabolism 33(9):808–813

19. Drost H, Spengler M, Gierlich C, Jahnke K (1980) Palatinit ein neuer Zuckeraustauschstoff: Untersuchungen bei Diabetikern vom Erwachsentyp [Palatinit a new sugar substitute: studies in adult-type diabetics]. Aktuelle Endokrinologie 2(171)

20. Sentko A, Willibald-Ettle I (2012) Isomalt. In: O'Donnell K, Kearsley MW (eds) Sweeteners and sugar alternatives in

food technology. Wiley, New York, pp 243–274

21. Martínez-Cervera S, Salvador A, Sanz T (2014) Comparison of different polyols as total sucrose replacers in muffins: Thermal, rheological, texture and acceptability properties. Food Hydrocolloids 35:1–8

22. EFSA Panel on Dietetic Products, Nutrition and Allergies (2011) Scientific Opinion on the substantiation of health claims related to the sugar replacers xylitol, sorbitol, mannitol, maltitol, lactitol, isomalt, erythritol, D-tagatose, isomaltulose, sucralose and polydextrose and maintenance of tooth mineralisation by decreasing tooth demineralisation (ID 463, 464, 563, 618, 647, 1182, 1591, 2907, 2921, 4300), and reduction of post-prandial glycaemic responses (ID 617, 619, 669, 1590, 1762, 2903, 2908, 2920) pursuant to Article 13(1) of Regulation (EC) No 1924/2006. EFSA Journal 9(4):2076:1–25

23. Holub I, Gostner A, Hessdörfer S, Theis S, Bender G, Willinger B et al. (2009) Improved metabolic control after 12-week dietary intervention with low glycaemic isomalt in patients with type 2 diabetes mellitus. Horm Metab Res. 41(12):886–892

24. Livesey G, Taylor R, Hulshof T, Howlett J (2008) Glycemic response and health – a systematic review and meta-analysis: Relations between dietary glycemic properties and health outcomes. Am J Clin Nutr 87(1):258S–268S

25. Jenkins DJA, Dehghan M, Mente A, Bangdiwala SI, Rangarajan S, Srichaikul K, et al. (2021) Glycemic Index, glycemic load, and cardiovascular disease and mortality. N Engl J Med 384(14):1312–1322

26. Atkinson FS, Brand-Miller JC, Foster-Powell K, Buyken AE, Goletzke J (2021) International tables of glycemic index and glycemic load values 2021: A systematic review. Am J Clin Nutr 114(5):1625–1632

27. Brannick B, Dagogo-Jack S (2018) Prediabetes and cardiovascular disease: Pathophysiology and interventions for prevention and risk reduction. Endocrinol Metab Clin North Am. 47(1):33–50

28. Forbes JM, Fotheringham AK (2017) Vascular complications in diabetes: old messages, new thoughts. Diabetologia 60(11):2129–2138