The final version of this paper was published in Journal of Food Science 22 January 2020

https://doi.org/10.1111/1750-3841.15007

Rate-All-That-Apply (RATA) Comparison of Taste Profiles for Different Sweeteners in Black Tea, Chocolate Milk and Natural Yogurt

*Vicki Tan Wei Kee[1], May Wee Sui Mei[1], Oliver Tomic[2], and Ciarán G. Forde[1,3]**

[1]Clinical Nutrition Research Center, A*STAR Singapore Institute for Clinical Sciences

[2]Faculty of Science and Technology, Norwegian University of Life Sciences, Ås, Norway

[3]Department of Physiology, Yong Loo Lin School of Medicine, National University of Singapore

Author for Correspondence*

Clinical Nutrition Research Centre

14 Medical Drive #07-02

MD 6 Building

Yong Loo Lin School of Medicine

Singapore 117599

Ciaran_Forde@sics.a-star.edu.sg

Word count: 4,792

Abstract

Growing health concerns have increased interest in reducing the consumption of added sugars, which can be achieved by substituting or replacing sugar with sweeteners to maintain sensory intensity and quality. The growing availability of sweeteners has increased the complexity of the perceptual landscape as sweeteners differ in the qualitative, intensity and temporal properties. A sweetener that can match the perceptual properties of sucrose in different food matrices is likely to have broad application. In complex foods, sweetness is influenced by the taste interactions with the existing tastants and possible matrix effects that influence release and perception of sweetness. The current study compared the taste properties of 3 food matrices (black tea, chocolate milk and natural yoghurt) sweetened by sucrose to those sweetened using 8 different sweeteners (acesulfame-K, aspartame, erythritol, *luo han guo* (Mogroside), palatinose (iso-maltulose), stevia (Reb-A), sucralose, sucrose-allulose mixture) using Rate-All-That-Apply. The sensory properties of each sweetener differed across matrices, with sucrose-allulose mixture, aspartame, erythritol, palatinose and sucralose having the most similar taste to sucrose across all foods. By contrast, acesulfame-K, stevia and *luo han guo* had taste profiles that most varied from sucrose, characterized by side tastes such as bitterness, chemical taste and a low sweetness. Sweeteners differed most from sucrose when presented in natural yoghurt compared to tea and chocolate milk. A food's taste properties can suppress sweetness intensity and promote undesirable side-tastes. Taken together, these findings highlight the importance of testing sweeteners in complex foods and help identify sweeteners and sweetener-combinations that can replicate the sweetness of sucrose and support sugar reduction.

Keywords

Sweeteners, sugar-reduction, side-taste, rate-all-that-apply

Practical Applications

Food manufacturers and researchers can refer to the results of the sensory profiles to identify suitable sweeteners substitutes for sucrose in foods with similar taste profiles to those tested. The current paper highlights important changes to a sweeteners sensory properties when presented in different complex foods, and provides an indication of the potential for calorie reduction by substituting sucrose with a range of low or no calorie sweeteners.

1. Introduction

Growing health concerns associated with obesity and type-2 diabetes has led to increased interest in reducing added sugars to food and beverages (Shankar, Ahuja, & Sriram, 2013). Reducing the sugar content of a product remains a challenge as low or poor quality sweetness can cause a decrease in acceptance (Hutchings, Low, & Keast, 2019). The availability of low or no-calorie sweeteners means it is possible to formulate foods and beverages that retain their sweetness at a substantially reduced sugar content. There are currently many commercially available sweeteners capable of matching the perceived sweetness intensity of sucrose (O'Brien-Nabors, 2016; Wee, Tan, & Forde, 2018), although they vary considerably in their sweetness quality, intensity, temporal properties and presence of side tastes (Fujimaru, Park, & Lim, 2012; Ketelsen, Keay, & Wiet, 1993; Reyes, Castura, & Hayes, 2017). These differences are often further amplified in food matrices with complex taste profiles, which studies comparing sweeteners in water may not accurately reflect (Fujimaru et al., 2012; Reyes et al., 2017; Zhao & Tepper, 2007).

In foods and beverages, sweeteners interact with the existing tastes and undergo taste-taste interactions that may suppress, mask or accentuate the sweetness intensity or presence of side tastes (de Cock, 1999; Reis et al., 2011; Rocha & Bolini, 2015). Tastant mixtures interact in complex food matrices and can lead to enhancement or suppression of individual taste qualities and impact the perception of undesirable side-tastes and product acceptance. Taste-taste interactions are not a factor when individual sweeteners are evaluated in water but they can produce significantly different taste profiles and therefore consumer acceptability for the same sweetener when tasted in mixtures as is often the case in foods or beverages (Keast & Breslin, 2003). When sweetness is present alongside an antagonistic bitter or sour taste, it can suppress and reduce overall sweetness intensity, while also releasing other side tastes from suppression to influence a product's overall flavour profile (Keast & Breslin, 2003; Lawless 1979). For example, when sweetener and blends were added to strawberry yoghurt at equivalent sweetness intensity to sucrose, the reformulated yoghurts had lower sweetness intensities compared to the sucrose-sweetened samples due to the acidity of the yoghurt (Reis et al., 2011). Sweetness can also dominate other taste qualities and suppress saltiness, bitterness and sourness (Green, Lim, Osterhoff, Blacher, & Nachtigal, 2010), especially at concentrations with moderate sweetness intensities.

The composition and texture of the food matrix can also influence perceived taste quality and intensity. Taste substances that stimulate sensations of sweet, sour, salty, bitter, and umami must first be released from the food or beverage matrix and dissolved in saliva before they can interact with taste receptors on the tongue. Fat and water in foods or beverages act as solvents for aroma and taste chemicals whereas proteins and carbohydrates can absorb and bind flavour chemicals and create a physical barrier between a tastant and taste receptors in the tongue (McGorrin & Leland, 1996; Taylor, 1999). Changes in product texture can significantly influence the release and perception of tastants in complex foods (Kokini, 1985) where increasing the viscosity of a matrix from liquid to semi-solid can reduce the perceived taste intensity of a taste compound (Moskowitz & Arabie, 1970; Pangborn, Gibbs, & Tassan, 1978). Taste-taste and taste-matrix effects are therefore important considerations when interpreting differences in perceived sweetness identified in water and extrapolating to the performance of these taste compounds in complex food matrices.

The current study sought to profile the perceived taste of sweeteners across three commonly sweetened and consumed foods using the Rate-All-That-Apply (RATA) method. The sweeteners included a range of nutritive and non-nutritive sweeteners, with varying temporal profiles, side-tastes (Tan, Wee, Tomic & Forde, 2019), and functionalities such as providing bulk or anti-glycaemic effects. The Rate-All-That-Apply (RATA) method is a variant of the Check-All-That-Apply approach and requires participants to rate the intensity only for the attribute terms that are perceived. Previous studies have characterized the dose-response (Wee, Tan, & Forde, 2018) and temporal sweet and side-taste profiles (Tan et. al., 2019) of sweeteners in water. To bridge the gap between understanding these sweeteners in water and their perceptual character in real-foods and beverages, the current study (i) compared the sensory profiles of different sweeteners to sucrose within each matrix, and (ii) evaluated the consistency of an individual sweetener across each matrix, in black tea, chocolate milk and natural yoghurt.

2. Materials and Methods

2.1 Participants

Participants were recruited from the National University of Singapore (n=20, 3 males) and were aged between 21 and 50 years old. All participants were screened for their ability to recognize and rate the intensity of the basic tastes (sweet, salty, bitter and salty) and had previously received extensive training and feedback during the sensory evaluation of sweeteners using both descriptive and temporal approaches (Tan et al., 2019; Wee et al., 2018). Participants were excluded if they were smokers, wore dentures, had sinus troubles, were on special diets, had specific food dislikes or had allergies or intolerances, had phenylketonuria, or were diabetic or pregnant. All participants provided informed consent and were compensated for their participation in the study. The study was approved by the National Healthcare Group Domain Specific Review Board (Reference Number: 2017/000787), Singapore and complies with the Declaration of Helsinki for research involving human subjects.

2.2 Samples

The three different food matrices selected were (1) unsweetened Darjeeling black tea (Kirin, Japan), (2) chocolate milk (6.43 g of cocoa powder (Hershey, Pennsylvania, USA) in 100 ml fresh milk (Farmhouse, Australia)) and (3) unsweetened natural yoghurt (Marigold, Singapore). These foods were chosen to represent different taste profiles to better understand how sweeteners are perceived in an astringent or bitter product (black tea), a product that has both sweet and bitter tastes (chocolate milk), and an acidic semi-solid food (natural yoghurt). All products are commonly consumed in Singapore and commercially available across a range of different sweetness levels, and therefore were familiar to participants in the current study. Products were also chosen to represent liquid (tea and chocolate milk) and semi-solid (yogurt) foods for an initial assessment of matrix effects on different sweeteners. A range of different sweeteners were chosen for comparison to represent natural and synthetic sweeteners of varied potency and caloric contents, and included acesulfame-K, aspartame, erythritol, *luo han guo* (Mogroside), palatinose (isomaltulose), stevia (Reb-A), sucralose, and sucrose. Sweetener concentrations were matched to the perceived sweetness intensity of a 10% sucrose solution, a concentration common in many commercial products (Ventura, Davis, & Goran, 2011) based on a previous dose-response study (Wee et. al., 2018) (Table 1). All samples were prepared at least 24 hours prior to each test session and refrigerated to keep fresh and samples were brought to room temperature prior to serving and evaluation.

Table 1 – Concentrations, energy density and source of sweeteners used in unsweetened black tea, chocolate milk and natural yogurt samples

Sweetener	Concentration* (%w/v)	Energy Density (kcal/g)	Source
Acesulfame-K	0.0832	0.0	Celanese, USA
Aspartame	0.0827	4.0	Suntop Enterprise, Singapore; 98.5%
Erythritol	13.3	0.2	iHerb, USA
Luo Han Guo (Mogroside)	0.0694	0.0	Hunan Huacheng Biotech Inc., China; 50.58%
Palatinose (Isomaltulose)	26.5	4.0	Beneo, France
Stevia (Rebaudioside-A)	0.0395	0.0	Suntop Enterprise, Singapore; 95.65%
Sucralose	0.0387	0.0	Tate & Lyle, USA; 99.9%
Sucrose-Allulose Mixture (1:1 weight)	10.7	2.1	Matsutani Co., Japan; 99.3% Allulose (d-psicose)
Sucrose	10.0	4.0	SIS, NTUC Fairprice, Singapore

**Rated as Equi-sweet concentrations to 10% w/v sucrose in water based on Wee et. al., (2018)*

2.3 Rate-All-That-Apply (RATA) Procedure

Participants attended study sessions at the sensory evaluation laboratory of Clinical Nutrition Research Center to complete screening, familiarization and test sessions. All participants had previously completed training and evaluation of sweetener samples, and had approximately 3-months experience with the sensory analysis of sweeteners. For the current trial, participants underwent training in the recognition and quantification of between 7-9 pre-defined sensory attributes for each food matrix. Participants initially completed pre-trial training sessions during which they were familiarized with the Rate-All-That-Apply (RATA) method, the test samples, and provisional descriptive vocabulary for each food matrix. The Rate-All-That-Apply (RATA) method is a consumer friendly approach that requires participants to select applicable attributes from a list, and rate their intensity (Ares et al., 2014). The RATA approach requires minimal training of panelists while at the same time enables sample description and discrimination (Giacalone & Hedelund, 2016). The initial attribute list and definitions were based on previous research on black tea (Alasalvar et al., 2012), chocolate milk (Thompson, Drake, Lopetcharat, & Yates, 2004) and natural yogurt (Coggins, Schilling, Kumari, & Gerrard, 2008). To reduce the risk of possible dumping, compression or smearing biases, the attributes for each test food were limited to the most relevant terms (Bennett & Hayes, 2012; van der Klaauw & Frank, 1996). The final attribute list, definitions and scale anchors for each food matrix were clarified and agreed upon by participants during familiarization (Table 2).

Sensory ratings for each food matrix were completed in separate test sessions, with a minimum of 24 hours between sessions. For each evaluation, a 10 ml sample of black tea or chocolate milk was presented in three-digit coded glass vials at room temperature, while natural yoghurt was served at refrigeration temperature (4°C) in a sample cup. Sample evaluation was standardised for each food such that participants placed the entire sample in their mouth and swirled for 5 seconds before swallowing and rating. In line with previous RATA approaches, participants were asked to rate the intensity of the terms that applied to the sample being tasted (Ares et al., 2014; Giacalone & Hedelund, 2016). A value of '0' was attributed by the experimenter for terms that were not rated by the participants. Presentation order of attributes were randomized across participants to avoid primacy bias and a one-minute break was enforced between samples to mitigate potential carry-over effects. Participants were instructed to cleanse their palate thoroughly with filtered water and water crackers (Carr's, United Kingdom) provided during the break. All samples with the 9 different sweeteners were evaluated in duplicate for each food matrix by all participants. Randomization of food products and sweeteners across participants were in accordance to William's (Latin Square) design to reduce presentation order and carry-over effects. All data was collected using computerized data acquisition software (CompuSense Cloud, Guelph, Ontario, Canada), in sensory booths which conform to international standards for the design of test rooms (ISO, 1988).

Table 2 – Attributes and definitions used for Rate-All-That-Apply (RATA) evaluations of sweetened black tea, chocolate milk and natural yogurt

Attributes	Definition
Black Tea	
Tea Flavour	The tea flavour associated with brewed tea products like Lipton tea and English Breakfast etc.
Bitterness	The bitter taste associated with bitter substances like caffeine
Astringent/ Mouth-drying	The drying, puckering sensation on the tongue and other mouth surfaces
Floral Taste	The floral taste associated with flowers like jasmine
Sourness	The sour taste associated with lemon
Sweetness	The sweet taste associated with table sugar in water
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Honey Taste	The taste associated with honey
Residual Sweetness	Lingering sweet taste associated with table sugar in water
Chocolate Milk	
Chocolate Flavour	The taste associated with cocoa
Dairy Flavour	The taste associated with dairy products like milk and cheese etc.
Malty	The malt taste associated with malt containing products like Milo, Ovaltine and Horlicks etc.
Bitterness	The bitter taste associated with bitter substances like caffeine
Powdery	The sensation of small particles like flour
Sweetness	The sweet taste associated with table sugar in water
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Honey Taste	The taste associated with honey
Residual Sweetness	Lingering sweet taste associated with table sugar in water
Yoghurt	
Creaminess	The mouthfeel associated with (whipped) cream
Sweetness	The sweet taste associated with table sugar in water
Sourness	The sour taste associated with lemon
Dairy flavour	The taste associate with dairy products like milk and cheese etc.
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Bitterness	The bitter taste associated with bitter substances like caffeine
Astringent/ Mouth-drying	The drying, puckering sensation on the tongue and other mouth surfaces
Residual sweetness	Lingering sweet taste associated with table sugar in water

2.4 Data Analysis

Normality and intra-class correlation tests were used to confirm the normality of data distribution and the reliability of duplicate ratings, and an average was taken for further analysis. Linear mixed model analysis using a maximum likelihood estimation to correct for assessor's effects was used to test the differences in the taste profile of each sweetener in each matrix. Significant main effects were compared using post-hoc Bonferroni test, and statistical significance was set at 5% (α=0.05). All statistical analysis was completed using SPSS (Version 23, Armonk, New York).

3. Results

3.1 Taste Profile of Sweeteners in Black Tea

The average attribute intensity for each sweetener in black tea is summarised in Figure 1, with the caloric content of each tea sample represented as a red dot (Kcal/100 g). Sucrose-sweetened black tea was characterized by a strong tea flavor, sweetness and a floral taste flavour with minimal side tastes (bitterness, chemical, astringency and sourness). There were no significant differences (p > 0.05) across sweeteners for the attributes *tea flavour*, *sweetness*, *astringency*, *floral taste*, and *residual sweetness*. Substitution of sucrose with acesulfame-K, stevia and *luo han guo* resulted in significantly higher *bitterness* and *chemical taste* ratings for these samples. The stevia sample also showed weak evidence of lower *honey taste* intensity ($p \leqslant 0.10$). Notably, the aspartame, sucralose, erythritol, palatinose and sucrose-allulose mixture samples had taste profiles that did not significantly differ from the sucrose sample. Comparison of each tea's caloric content highlights that aspartame, sucralose, erythritol and sucrose-allulose mixture had the most potential to reduce calories (50-100%) while maintaining a similar taste experience to a sucrose sweetened black tea. Palatinose has a similar taste profile to sucrose but with double the calories of the sucrose sweetened tea (red dots, Figure 1).

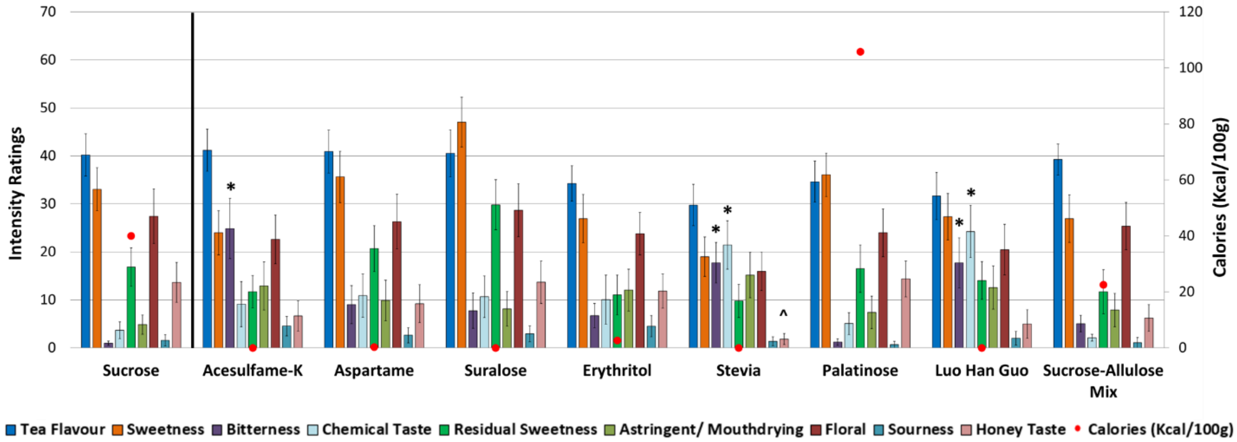

Figure 1 - Taste profiles for the sweeteners in black tea where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars above each average represent the standard error of the mean (SEMs).

3.2 Taste Profile of Sweeteners in Chocolate Milk

The taste profiles of chocolate milk samples are presented in Figure 2. Chocolate milk sweetened with sucrose was characterized by a strong *chocolate flavor*, moderate *sweetness*, *dairy* and *malty taste*, with low *bitterness*, *chemical taste* and *residual sweetness*. The sweetener samples did not significantly differ in *chocolate flavour*, *dairy flavour*, *malty* or *honey taste* and *sweetness* was equivalent for all samples with the exception of stevia, which was rated significantly less *sweet* (p > 0.05). The stevia sweetened chocolate milk was significantly higher ($p \leq 0.05$) in perceived *bitterness*, with acesulfame-K also rated more *bitter* than sucrose (non-significant). Both stevia and *luo han guo* samples had significantly higher *chemical taste* ratings, as was reported in the black tea samples. In a similar finding to the black tea comparison, aspartame, sucralose, erythritol, palatinose and sucrose-allulose mixture all had taste profiles that did not significantly differ from the sucrose-sweetened chocolate milk. Comparison of the calorie content of each chocolate milk shows aspartame, sucralose, erythritol and sucrose-allulose mixture can deliver an equivalent sensory profile to profile to sucrose, with between 50-100% reduction in calories. Palatinose had a similar sensory profile to sucrose but higher caloric content.

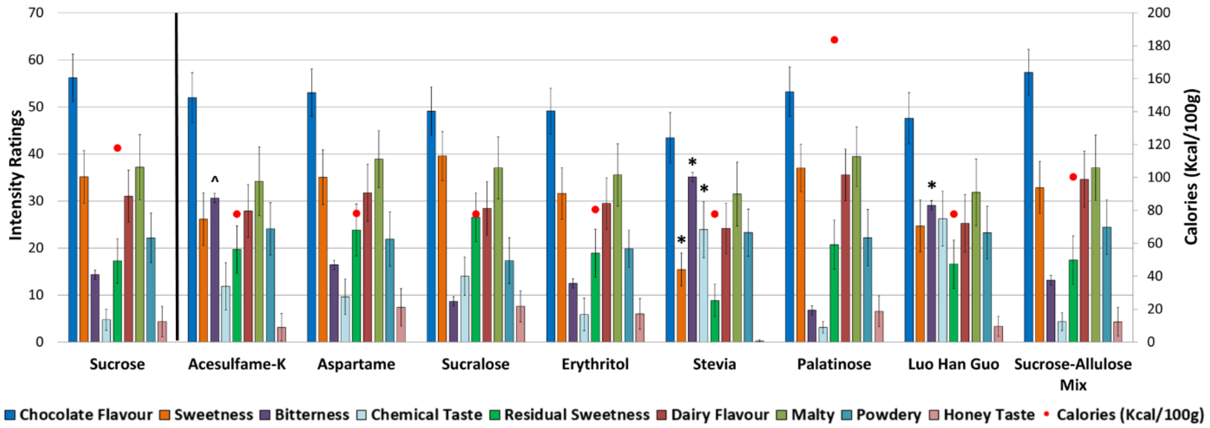

Figure 2 - Taste profiles for sweeteners in chocolate milk where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars represent the standard error of the mean (SEMs).

3.3 Taste Profile of Sweeteners in Natural Yoghurt

The taste profiles of chocolate milk samples are presented in Figure 3, with the caloric values of each sample represented as a red dot (kcal/100g). Yogurt sweetened with sucrose had a strong *dairy* flavor, high *sweetness*, *creaminess* and *sourness*, and was low in *bitterness*, *chemical taste* and *astringency*' (Figure 3). There were no significant differences in *dairy flavour*, *creaminess* or *sourness* between samples sweetened with sucrose and those with added sweetener. Acesulfame-K, stevia, and *luo han guo* had a lower rated *sweetness* intensity compared to sucrose. This is likely due to the presence of side tastes in these three sweeteners including a higher *chemical taste* and *bitterness* in the acesulfame-K yogurt sample. The aspartame, sucralose, palatinose and sucrose-allulose mixture samples had taste profiles that were most similar to sucrose, with no significant differences ($p > 0.05$) in attribute ratings compared to sucrose. Comparison of the calorie contents of each chocolate milk shows that if sucrose were replaced with aspartame, sucralose or the sucrose-allulose mixture there is scope to significantly reduce total caloric content. Palatinose had a similar taste profile to sucrose, but with higher calorie content.

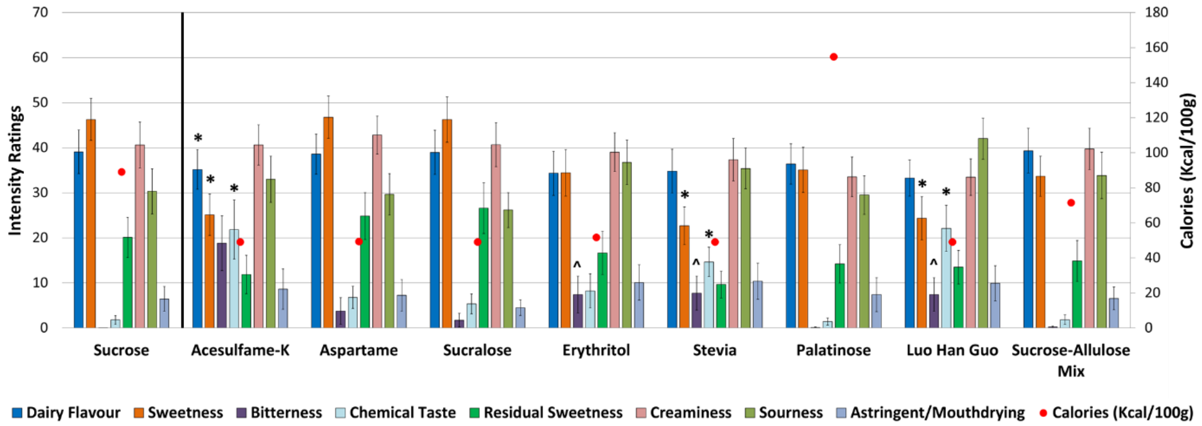

Figure 3 - Taste profiles for sweeteners in natural yogurt where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars represent the standard error of the mean (SEMs).

4. Discussion

Findings from the current study show opportunities to match the sweetness profile of sucrose in three different foods, and at the same time reduce their caloric contents. The results highlight the impact of the taste properties of each food matrix on the perceptual properties of sweeteners, with significant differences in chemical and bitter side tastes emerging for among sweeteners in some foods.

The three food matrices compared in the current study provide an opportunity to examine sweetener taste profiles against a backdrop of products with a bitter/tannic (black tea), sweet/bitter (chocolate milk) and sour/acidic (natural yoghurt) basic taste profiles. This enabled a comparison of the versatility of different sweetener alternatives, with potential for a wider application for sweeteners that are capable of consistently replicating the sweetness quality and intensity of sucrose in products with different basic taste profiles. Aspartame, sucralose, palatinose and sucrose-allulose mixture consistently produced a similar taste profile to sucrose across all three food matrices tested in the current study. Conversely, acesulfame-K, stevia and *luo han guo* consistently varied from sucrose with greater perceived bitterness and chemical taste. Differences in the taste profiles of these sweeteners were most apparent when compared in the natural yoghurt samples, which may be due to the strongly acidic taste profile of yoghurt. Sourness can enhance the perception of bitterness by suppressing sweetness, and releasing bitterness from suppression (Kamen, Pilgrim, Gutman, & Kroll, 1961). A higher intensity of bitter side tastes can reduce sweetness perception as seen in the lower sweetness intensity ratings for acesulfame-K, stevia, and *luo han guo* in yoghurt (Green, Lim et al., 2010; Reis, Minim et al., 2011).

A higher viscosity can contribute to a reduction in taste intensity by slowing the release of tastants into the saliva for dissolution and perception (Baines & Morris, 1987; Moskowitz & Arabie, 1970; Pangborn, Trabue, & Szczesniak, 1973). These 'food matrix' effects would occur across all tastants, as the consistency of a matrix can reduce tastant mobility and perceived intensity (Calviño et al., 1993). The current study showed little effect of matrix viscosity as the rated taste intensity was equivalent between the two liquid samples (tea and chocolate milk) and the thicker semi-solid yogurt sample. To fully explore the impact of different food physicochemical properties on the release profile of different sweeteners, it is likely that larger differences in food matrix textures would be required. One should also consider the physical binding properties of these sweeteners to matrices which may influence the taste perception of the final product (Tenney, Hayes, Euston, Elias, & Coupland, 2017). In this regard, differences in rated taste intensity of sweeteners were more impacted by the background taste of each food matrix than the smaller differences in product viscosity and binding properties.

In complex food matrices, antagonistic side tastes can be promoted or suppressed from within the existing taste profile of the food or by the sweetener that is used to replace sucrose. Sucrose can mask side tastes in a complex food, but cannot be assumed that at equi-sweet concentrations, sweeteners will have the same masking effect on side-tastes. The presence of other taste components may also have an impact on the sweetness perception of an end product. (Green et al., 2010). Increased intensity of these side tastes in chocolate milk sweetened with acesulfame-K, stevia and *luo han guo* was associated with a reduction in sweetness, due to the suppression of sweetness in the presence of these antagonistic tastes (Calviño, García-Medina, Cometto-Muniz, & Rodríguez, 1993; Green et al., 2010). Previous research has shown that when stevia is used to replace sucrose in tea it produced an artificial sweet taste associated with metallic and bitter aftertastes (Majchrzak, Ipsen, & Koenig, 2015). In agreement with previous findings, *luo han guo* and stevia were found to have higher bitterness and chemical taste (Li, Lopetcharat, & Drake, 2015). High potency sweeteners such as sucralose and stevioside in chocolates were also associated with greater bitterness and bitter aftertaste (de Melo, Bolini, & Efraim, 2009). Despite claims of these aversive side tastes, perception of bitterness in non-nutritive sweeteners such as Rebaudioside A and D, and acesulfame-K were noted to vary in individual due to the polymorphism of the taste receptors (Allen, McGeary, & Hayes, 2013; Bobowski, Reed, & Mennella, 2016). The bulk sweetener erythritol has not previously been reported to have unpleasant side taste (Fujimaru et al., 2012; Tan et. al., 2019) and in the current study had a similar taste profile to sucrose in both black tea and chocolate milk, but trended to having a higher bitter intensity in natural yoghurt. Previous research has shown that the taste profiles of orange juices sweetened with stevia were dominated by a higher intensity of bitterness and off-flavours (Zorn, Alcaire, Vidal, Giménez, & Ares, 2014). Similarly, strawberry-flavoured yoghurts sweetened with either stevia or acesulfame-K had reduced sweetness and an altered strawberry flavour (Reis et al., 2011).

The current trial highlights the potential for aspartame, sucralose, erythritol, palatinose and sucrose-allulose mixture to offer potential calorie savings while reproducing a similar taste profile to sucrose. The polyol and allulose-mixture samples also offer bulking properties (Livesey, 2003) which provides additional functionality for low-sugar products in terms of water binding and texture. The net benefit of substituting sucrose with one sweetener over another should be considered in terms of the product reformulation goals. For example, if the target is to reduce product glycaemia, then there are reported metabolic benefits to reformulation with evidence of an anti-glycaemic effect for allulose (Chung, Oh, & Lee, 2012) and palatinose (iso-maltulose) (Holub et al., 2010). However, if the focus of reformulation is to reduce energy from sucrose, then some sweeteners are better positioned to meet this target for partial (allulose-sucrose mixture) or complete (sucralose) energy reduction. Despite a similar taste profile to sucrose, the palatinose-sweetened sample would not support a calorie reduction, as to match the sweetness intensity of a 10% w/v sucrose solution, palatinose needs to be added at a concentration that increases caloric content. The current study highlights the diverse sensory properties of the sweeteners profiled. A recent study has highlighted the varied effect different sweeteners have on energy balance and body weight. In the trial, weight changes were compared following daily consumption of four different sweeteners used to replace sucrose in a beverage. Longer-term exposure to these sweeteners revealed variability in their effect on body weight, with people losing most weight when consuming sucralose followed by stevia (Reb-A) and aspartame, while those consuming sucrose and saccharin gained weight (Higgins & Mattes, 2019). The sweetener specific effect of sucrose replacement on body weight demonstrates that in addition to the variability in their sensory profiles, not all sweeteners are likely to have the same anticipated beneficial effects on body weight. Future efforts to categorize sweeteners should consider their distinct sensory profiles and metabolic effect, rather than referring to such a diverse group of compounds as simply 'non-nutritive' or 'low-calorie' alternative sweeteners.

The sucrose-allulose mixture was the only sweetener blend in the current study and it consistently delivered a similar sensory profile to sucrose, while reducing nearly half the calories. Sweetener blends have previously been proposed as a better alternative to straight replacement of sucrose with an individual sweetener (Ayya & Lawless, 1992; Hanger, Lotz, & Lepeniotis, 1996), as this approach can be used to optimize the synergy between two sweeteners and can mask undesirable side-tastes. In a recent comparison of the same sweeteners used in the current study, Tan et al. (2019) showed that allulose alone had a low sweetness intensity with increased bitterness and chemical taste, whereas when blended 1:1 with sucrose, had the same temporal and qualitative profile as sucrose. In the current study, acesulfame-K consistently had strong bitter and chemical side-tastes, but previous findings show that when blended with aspartame in a dairy (Lassi) drink, the blend produced a taste profile similar to sucrose (George, Arora, Wadhwa, Singh, & Sharma, 2010). Further research is needed to identify the sweetener blends with required sensory profiles to replace or reduce sucrose in different food matrices, while concurrently optimizing the post-ingestive metabolic impact of product consumption.

5. Conclusion

The current study described differences in the sensory profiles of a range of sweeteners across three food matrices, highlighting both the consistency and variability of their profiles in comparison to sucrose. These findings emphasize the importance of considering the taste of other food ingredients in a food and for potential matrix effects to alter the sensory properties of a sweetener. Findings from the current study show that aspartame, sucralose, erythritol, palatinose and sucrose-allulose mixture had the most similar taste profiles to sucrose across all matrices and afford an opportunity to reduce sucrose content while maintaining a similar taste profile to the original sugar sweetened product. Acesulfame-K, stevia and *luo han guo* had profiles that varied most from sucrose, with significantly higher bitterness, chemical taste and lower sweetness perceived. Future studies should consider the potential to blend these low and no-calorie sweeteners to optimize their taste profiles in complex foods and exploit the opportunity to reduce the sugar content of complex foods and beverages.

Acknowledgements

We would like to thank the following companies for providing some of the sweetener samples for this study: Roquette, Matsutani and Beneo.

Conflicts of interest

CGF has received reimbursements for speaking at conferences sponsored by companies selling nutritional products and currently serves on the scientific advisory council of a commercial ingredient manufacturer. All other authors declare no conflicts of interest.

Authors Contribution

C.G. Forde conceived and designed the experiments. V.W.K. Tan collected the data. V.W.K. Tan, O. Tomic and C.G. Forde analyzed the data. V.W.K. Tan and C.G. Forde prepared the manuscript. All authors contributed to the final version of the manuscript.

References

Alasalvar, C., Topal, B., Serpen, A., Bahar, B., Pelvan, E., & Gökmen, V. (2012). Flavor characteristics of seven grades of black tea produced in Turkey. *Journal of agricultural and food chemistry, 60*(25), 6323-6332.

Allen, A. L., McGeary, J. E., & Hayes, J. E. (2013). Rebaudioside A and rebaudioside D bitterness do not covary with acesulfame-K bitterness or polymorphisms in TAS2R9 and TAS2R31. *Chemosensory perception, 6*(3), 109-117.

Ares, G., Bruzzone, F., Vidal, L., Cadena, R. S., Giménez, A., Pineau, B., . . . Jaeger, S. R. (2014). Evaluation of a rating-based variant of check-all-that-apply questions: Rate-all-that-apply (RATA). *Food Quality and Preference, 36*, 87-95.

Ayya, N., & Lawless, H. T. (1992). Quantitative and qualitative evaluation of high-intensity sweeteners and sweetener mixtures. *Chemical Senses, 17*(3), 245-259.

Baines, Z. V., & Morris, E. R. (1987). Flavour/taste perception in thickened systems: the effect of guar gum above and below c. *Food Hydrocolloids, 1*(3), 197-205.

Bennett, S. M., & Hayes, J. E. (2012). Differences in the chemesthetic subqualities of capsaicin, ibuprofen, and olive oil. *Chemical Senses, 37*(5), 471-478.

Bobowski, N., Reed, D. R., & Mennella, J. A. (2016). Variation in the TAS2R31 bitter taste receptor gene relates to liking for the nonnutritive sweetener Acesulfame-K among children and adults. *Scientific reports, 6*, 39135.

Calviño, A. M., García-Medina, M. R., Cometto-Muniz, J. E., & Rodríguez, M. B. (1993). Perception of sweetness and bitterness in different vehicles. *Perception & psychophysics, 54*(6), 751-758.

Chung, M.-Y., Oh, D.-K., & Lee, K. W. (2012). Hypoglycemic health benefits of D-psicose. *Journal of agricultural and food chemistry, 60*(4), 863-869.

Coggins, P. C., Schilling, M. W., Kumari, S., & Gerrard, P. D. (2008). Development of a sensory lexicon for conventional milk yogurt in the United States *Journal of sensory studies, 23*(5), 671-687. doi:doi:10.1111/j.1745-459X.2008.00179.x

de Cock, P. (1999). Erythritol: a novel noncaloric sweetener ingredient *Low-Calories Sweeteners: Present and Future* (Vol. 85, pp. 110-116): Karger Publishers.

de Melo, L. L. M. M., Bolini, H. M. A., & Efraim, P. (2009). Sensory profile, acceptability, and their relationship for diabetic/reduced calorie chocolates. *Food Quality and Preference, 20*(2), 138-143.

Fujimaru, T., Park, J. H., & Lim, J. (2012). Sensory characteristics and relative sweetness of tagatose and other sweeteners. *Journal of food science, 77*(9), S323-S328.

George, V., Arora, S., Wadhwa, B. K., Singh, A. K., & Sharma, G. S. (2010). Optimisation of sweetener blends for the preparation of lassi. *International journal of dairy technology, 63*(2), 256-261.

Giacalone, D., & Hedelund, P. I. (2016). Rate-all-that-apply (RATA) with semi-trained assessors: An investigation of the method reproducibility at assessor-, attribute-and panel-level. *Food Quality and Preference, 51*, 65-71.

Green, B. G., Lim, J., Osterhoff, F., Blacher, K., & Nachtigal, D. (2010). Taste mixture interactions: suppression, additivity, and the predominance of sweetness. *Physiology & behavior, 101*(5), 731-737.

Hanger, L., Lotz, A., & Lepeniotis, S. (1996). Descriptive profiles of selected high intensity sweeteners (HIS), HIS blends, and sucrose. *Journal of food science, 61*(2), 456-459.

Higgins, K. A., & Mattes, R. D. (2019). A randomized controlled trial contrasting the effects of 4 low-calorie sweeteners and sucrose on body weight in adults with overweight or obesity. *The American journal of clinical nutrition, 109*(5), 1288-1301.

Holub, I., Gostner, A., Theis, S., Nosek, L., Kudlich, T., Melcher, R., & Scheppach, W. (2010). Novel findings on the metabolic effects of the low glycaemic carbohydrate isomaltulose (Palatinose™). *British journal of nutrition, 103*(12), 1730-1737.

Hutchings, S. C., Low, J. Y., & Keast, R. S. (2019). Sugar reduction without compromising sensory perception. An impossible dream? Critical reviews in food science and nutrition, 59(14), 2287-2307.

ISO. (1988). Sensory analysis: General guidance for the design of test rooms. Geneva, Switzerland: International Organization for Standardization.

Kamen, J. M., Pilgrim, F. J., Gutman, N. J., & Kroll, B. J. (1961). Interactions of supratheresshold taste stimuli. *Journal of Experimental Psychology, 62*(4), 348.

Keast, R. S., & Breslin, P. A. (2003). An overview of binary taste–taste interactions. *Food Quality and Preference, 14*(2), 111-124.

Ketelsen, S., Keay, C., & Wiet, S. (1993). Time‐intensity parameters of selected carbohydrate and high potency sweeteners. *Journal of food science, 58*(6), 1418-1421.

Kokini, J. (1985). Fluid and semi-solid food texture and texture-taste interactions. *Food technology (USA)*.

Lawless, H. T. (1979). Evidence for neural inhibition in bittersweet taste mixtures. *Journal of comparative and physiological psychology, 93*(3), 538.

Li, X., Lopetcharat, K., & Drake, M. (2015). Parents' and children's acceptance of skim chocolate milks sweetened by monk fruit and stevia leaf extracts. *Journal of food science, 80*(5), S1083-S1092.

Livesey, G. (2003). Health potential of polyols as sugar replacers, with emphasis on low glycaemic properties. *Nutrition Research Reviews, 16*(2), 163-191.

Majchrzak, D., Ipsen, A., & Koenig, J. (2015). Sucrose-replacement by rebaudioside a in a model beverage. *Journal of food science and technology, 52*(9), 6031-6036.

McGorrin, R. J., & Leland, J. V. (1996). *Flavor-food interactions*: ACS Publications.

Moskowitz, H. R., & Arabie, P. (1970). Taste intensity as a function of stimulus concentration and solvent viscosity. *Journal of Texture Studies, 1*(4), 502-510.

O'Brien-Nabors, L. (2016). *Alternative sweeteners*: CRC Press.

Pangborn, R. M., Gibbs, Z. M., & Tassan, C. (1978). Effect of hydrocolloids on apparent viscosity and sensory properties of selected beverages 1 *Journal of Texture Studies, 9*(4), 415-436.

Pangborn, R. M., Trabue, I. M., & Szczesniak, A. S. (1973). Effect of hydrocolloids on oral viscosity and basic taste intensities. *Journal of Texture Studies, 4*(2), 224-241.

Reis, R. C., Minim, V. P., Bolini, H. M., Dias, B. R., Minim, L. A., & Ceresino, E. B. (2011). Sweetness equivalence of different sweeteners in strawberry‐flavored yogurt. *Journal of Food Quality, 34*(3), 163-170.

Reyes, M. M., Castura, J. C., & Hayes, J. E. (2017). Characterizing dynamic sensory properties of nutritive and nonnutritive sweeteners with temporal check‐all‐that‐apply. *Journal of sensory studies, 32*(3), e12270.

Rocha, I. F. d. O., & Bolini, H. M. A. (2015). Passion fruit juice with different sweeteners: sensory profile by descriptive analysis and acceptance. *Food science & nutrition, 3*(2), 129-139.

Shankar, P., Ahuja, S., & Sriram, K. (2013). Non-nutritive sweeteners: Review and update. *Nutrition, 29*(11–12), 1293-1299. doi:http://dx.doi.org/10.1016/j.nut.2013.03.024

Tan, V. W. K., Wee, M. S. M., Tomic, O., & Forde, C. G. (2019). Temporal sweetness and side tastes profiles of 16 sweeteners using temporal check-all-that-apply (TCATA). *Food Research International*.

Tenney, K., Hayes, J., Euston, S., Elias, R., & Coupland, J. (2017). Binding of caffeine and quinine by whey protein and the effect on bitterness. *Journal of food science, 82*(2), 509-516.

Taylor, A. (1999). Flavour matrix interactions *Current Topics in Flavours and Fragrances* (pp. 123-138): Springer.

Thompson, J. L., Drake, M. A., Lopetcharat, K., & Yates, M. D. (2004). Preference Mapping of Commercial Chocolate Milks. *Journal of food science, 69*(9), S406-S413. doi:doi:10.1111/j.1365-2621.2004.tb09958.x

van der Klaauw, N. J., & Frank, R. A. (1996). Scaling component intensities of complex stimuli: the influence of response alternatives. *Environment international, 22*(1), 21-31.

Ventura, E. E., Davis, J. N., & Goran, M. I. (2011). Sugar content of popular sweetened beverages based on objective laboratory analysis: focus on fructose content. *Obesity, 19*(4), 868-874.

Wee, M., Tan, V., & Forde, C. (2018). A Comparison of Psychophysical Dose-Response Behaviour across 16 Sweeteners. *Nutrients, 10*(11), 1632.

Zhao, L., & Tepper, B. J. (2007). Perception and acceptance of selected high-intensity sweeteners and blends in model soft drinks by propylthiouracil (PROP) non-tasters and super-tasters. *Food Quality and Preference, 18*(3), 531-540.

Zorn, S., Alcaire, F., Vidal, L., Giménez, A., & Ares, G. (2014). Application of multiple-sip temporal dominance of sensations to the evaluation of sweeteners. *Food Quality and Preference, 36*, 135-143.

Table 3 – Concentrations, energy density and source of sweeteners used in unsweetened black tea, chocolate milk and natural yogurt samples

Sweetener	Concentration* (%w/v)	Energy Density (kcal/g)	Source
Acesulfame-K	0.0832	0.0	Celanese, USA
Aspartame	0.0827	4.0	Suntop Enterprise, Singapore; 98.5%
Erythritol	13.3	0.2	iHerb, USA
Luo Han Guo (Mogroside)	0.0694	0.0	Hunan Huacheng Biotech Inc., China; 50.58%
Palatinose (Isomaltulose)	26.5	4.0	Beneo, France
Stevia (Rebaudioside-A)	0.0395	0.0	Suntop Enterprise, Singapore; 95.65%
Sucralose	0.0387	0.0	Tate & Lyle, USA; 99.9%
Sucrose-Allulose Mixture (1:1 weight)	10.7	2.1	Matsutani Co., Japan; 99.3% Allulose (d-psicose)
Sucrose	10.0	4.0	SIS, NTUC Fairprice, Singapore

**Rated as Equi-sweet concentrations to 10% w/v sucrose in water based on Wee et. al., (2018)*

Table 4 – Attributes and definitions used for Rate-All-That-Apply (RATA) evaluations of sweetened black tea, chocolate milk and natural yogurt

Attributes	Definition
Black Tea	
Tea Flavour	The tea flavour associated with brewed tea products like Lipton tea and English Breakfast etc.
Bitterness	The bitter taste associated with bitter substances like caffeine
Astringent/ Mouth-drying	The drying, puckering sensation on the tongue and other mouth surfaces
Floral Taste	The floral taste associated with flowers like jasmine
Sourness	The sour taste associated with lemon
Sweetness	The sweet taste associated with table sugar in water
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Honey Taste	The taste associated with honey
Residual Sweetness	Lingering sweet taste associated with table sugar in water
Chocolate Milk	
Chocolate Flavour	The taste associated with cocoa
Dairy Flavour	The taste associated with dairy products like milk and cheese etc.
Malty	The malt taste associated with malt containing products like Milo, Ovaltine and Horlicks etc.
Bitterness	The bitter taste associated with bitter substances like caffeine
Powdery	The sensation of small particles like flour
Sweetness	The sweet taste associated with table sugar in water
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Honey Taste	The taste associated with honey
Residual Sweetness	Lingering sweet taste associated with table sugar in water
Yoghurt	
Creaminess	The mouthfeel associated with (whipped) cream
Sweetness	The sweet taste associated with table sugar in water
Sourness	The sour taste associated with lemon
Dairy flavour	The taste associate with dairy products like milk and cheese etc.
Chemical Taste	The chemical taste that resembles artificial flavours, medicinal or chemical substances
Bitterness	The bitter taste associated with bitter substances like caffeine
Astringent/ Mouth-drying	The drying, puckering sensation on the tongue and other mouth surfaces
Residual sweetness	Lingering sweet taste associated with table sugar in water

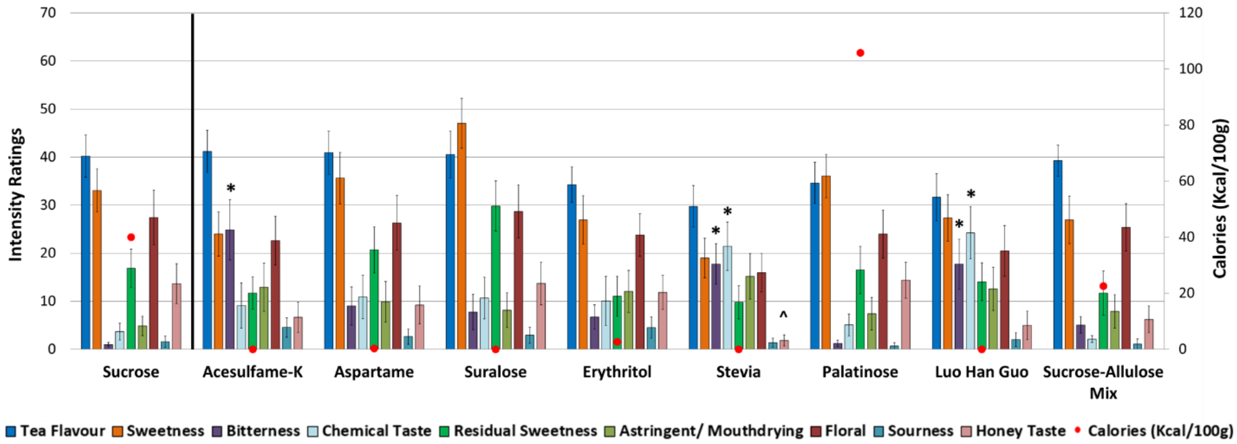

Figure 4 - Taste profiles for the sweeteners in black tea where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars above each average represent the standard error of the mean (SEMs).

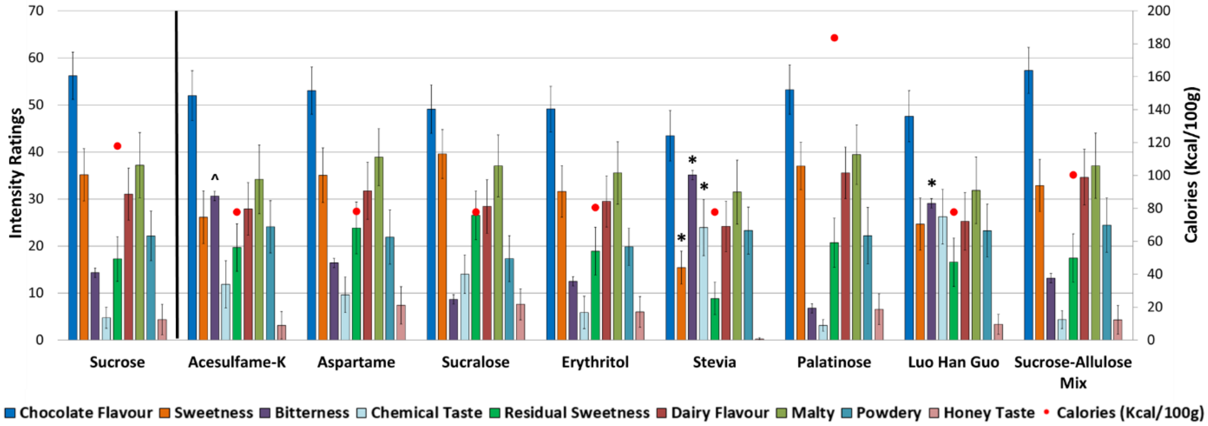

Figure 5 - Taste profiles for sweeteners in chocolate milk where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars represent the standard error of the mean (SEMs).

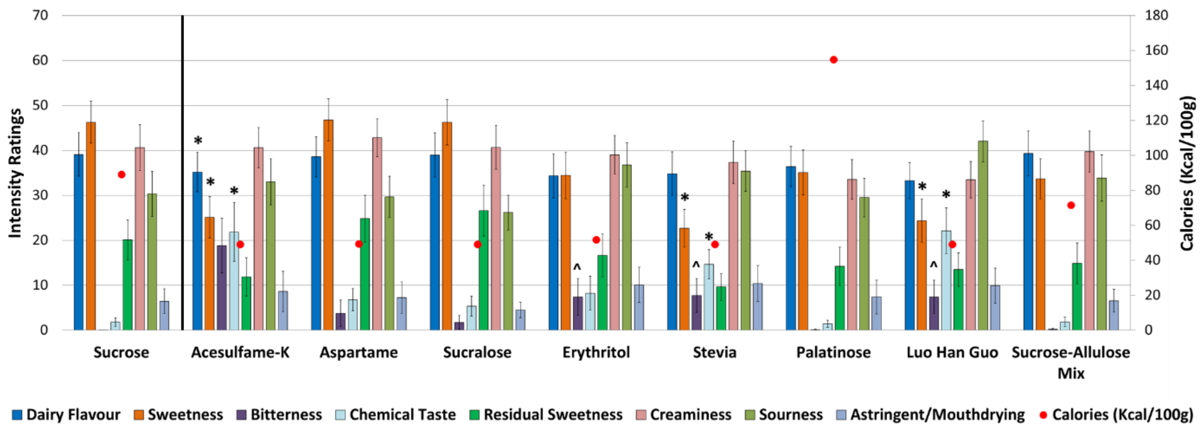

Figure 6 - Taste profiles for sweeteners in natural yogurt where (*) indicates significant differences between the attribute intensity and that of the sucrose sweetened sample ($p \leqslant 0.05$) and (^) indicates weak significance ($p \leqslant 0.10$). Vertical bars represent the standard error of the mean (SEMs).