NFS Journal 23 (2021) 44–51

Contents lists available at ScienceDirect

NFS Journal

journal homepage: www.elsevier.com/locate/nfs

Study of different technological strategies for sugar reduction in muffin addressed for children

Rossella Caporizzi, Carla Severini, Antonio Derossi *

Department of Agriculture, Food, Natural Resources and Engineering (DAFNE), University of Foggia, Foggia, Via Napoli 25, Italy

ARTICLE INFO

Keywords:
Sugar reduction
Muffin
Spatial distribution
Multisensory interaction
Vanillin

ABSTRACT

To exceed in sugar consumption is one of the main causes of overweight and obesity, especially for children and adolescent. However, sugar reduction, especially in baked goods, is challenging due to its effect not only on sensorial properties but also for other quality parameters.

Multiple technological strategies to obtain muffins at low sugar content addressed for children were studied. Specifically, the inhomogeneous spatial distribution of sucrose (1, 3 and 5 layers of food formula at different sugar content), the taste enhancement by vanillin addition (0, 1 and 2%) and the use of different particle size of sugar (200, 400 and 600 μm) were investigated through a Box-Behnken design. Physical attributes were negatively affected by spatial distribution due to the substantial role of sucrose in the expansion of muffins. Indeed, maximum height of homogeneous muffins was of 37.8 ± 3.9 mm, while in inhomogeneous samples reached values of ≈ 30 mm. The low expansion of inhomogeneous muffins was also attested by porosity fraction which notably decreased from 68.2% in 1-layer muffin to 58.4% and 65.6% in 3-layers and 5-layers muffins, respectively. The perception of sweetness was improved for the inhomogeneous muffins and with a mass fraction of added vanillin at 1% confirming its great potential as taste enhancer, especially when using particle size of sugar less than 400 μm. Based on sensorial and physical data, stratified muffins with 3 layers, a mass fraction of added vanillin at 1% and sugar particle size in the range between 200 and 600 μm, showed excellent results. The proposed strategy could be used to design and develop innovative muffins designed for children contributing in the reduction of sugar intake in the daily diet.

1. Introduction

The World Health Organization recently published alarming data that reveal as 41 million children under the age of 5 are overweight or obese, and the tight relation of these issues with increased habits toward the excessive sugar intake [1]. The unconscionable sugar consumption in the diet is of concern also because it is associated with adverse health effects, e.g. dental caries, type 2 diabetes, cardiovascular diseases, etc., especially among children and adolescents [2–5].

In this context, a decrease of the free sugar consumption to less than 10% of the total daily energy intake is strongly and widely recommended from national and international public entities [6,7]. Alarmingly, to date, WHO directives are not achieved although many governments have supported some initiatives to reduce the consumption of sugar-rich foods and/or beverages, with sugar tax or traffic light to be the most remarkable ones [8,9]. Greatest chance to tackle this challenge includes strategies which do not require consumers' willpower to change their eating habits so, actions that directly limit the introduction of sugars in foods and beverages could be more effective [2].

Sugar reduction or its total removal in bakery products is an important goal for food industry [10]. The most used strategy is product reformulation achieved by partial or total replacement with different sweeteners or just reducing the total sugar amount [11]. Regarding sugar replacement, high-intensity sweeteners with 'zero' or very low calories are commonly used because they bind on the taste receptors on the tongue generating in the brain the signal of sweeteners [8]. However, the use of sugar substitutes can convey bitter and metallic off-flavour as well as the need to incorporate in the food formula bulking agents, in order to ensure the product quality in terms of appearance, texture, volume, etc. [8,12]. Actually, sucrose, apart from providing sweetness, performs some important quality-related functionalities such as the bulk of the baked products by incorporation and stabilization of air bubble and by acting on gluten development, moisture retention, extension of shelf life by decreasing water activity thereby inhibiting

* Corresponding author.
E-mail address: antonio.derossi@unifg.it (A. Derossi).

https://doi.org/10.1016/j.nfs.2021.04.001
Received 6 August 2020; Received in revised form 12 April 2021; Accepted 21 April 2021
Available online 26 April 2021

microorganisms growth, colour of the crust due to Maillard reaction and caramelization, texture properties (e.g. crispness for biscuits or tenderness for cakes and muffins) as well as it affects freezing point [3,5,11,13]. For all these reasons sugar reduction and/or replacement remains a challenge for food manufacturers because it definitely prejudices the overall quality of food and reduce consumers' acceptance [14].

In the last years, some innovative strategies have emerged to overcome the aforementioned problems. A possible option is the use of multisensory integration principles that involves the addition of appropriate aromas capable to enhance the sweet intensity due to complex cross-modal interactions. For instance, sweetness perception has been enhanced by the addition of aromas related to sweet products, such as vanilla, caramel or fruity notes, albeit cross-modal aroma–taste interactions have been reported to be aroma- and product-specific [15,16]. However, this approach has been adopted mainly for salt reduction as widely reported by Stieger and van de Velde [17].

Another cutting-edge approach is the creation of food structure with an inhomogeneous spatial distribution of sugar that alters the sensory profile [18]. Apart from studies that analysed salt reduction with this approach, to the authors knowledge only few data are available for application with sugar. Holm et al. [18] studied the effect of sugar distribution on sweetness, hardness ad breakdown behaviour in gelatin gels, demonstrating the effectiveness of this strategy in perceived sweetness. Later, Dadali and Elmaci [13] applied the inhomogeneous distribution of sugar on a cake with positive results on sweetness perception even though some drawbacks on physical properties were observed.

Finally, a recent study proposed a new strategy based on the manipulation of sugar particle size [5]. Authors findings proved that samples – chocolate brownies - formulated with the smallest sugar particles, with diameter in the range of 459 and 972 μm, were perceived as the sweetest sample when compared with brownies formulated with bigger sugar particles. Moreover, such samples were the softest and moistest, attesting also a good consumers' acceptability.

However, further information on these innovative strategies would be of great importance on the production of food at reduced sugar content and with highly acceptable sensorial properties.

The aim of this study was to investigate the combined effect of three innovative strategies – inhomogeneous spatial distribution of sugar, taste enhancement with vanillin and different particle size of sugar - on physical and sensorial properties of muffin with reduced sugar content addressed for children.

2. Materials and methods

2.1. Ingredients preparation

Food ingredients used in this trial were: wheat flour 00 (Coop, Itlay), sugar (Notadolce, Italy), whole-milk yogurt with apricot aroma (Parmalat, Italy), sunflower oil (Coop, Italy), eggs (le Naturelle, Italy), baking powder (Pane degli Angeli, Italy), vanillin (Pane degli Angeli, Italy), food grade blue colorant (Pane degli Angeli, Italy). All ingredients were purchased from a local grocery store in Foggia, Italy.

Wheat flour was forced to pass through a 400 μm certified sieve (Test Sieve, Retsch, Germany) before using for muffin preparation. Sugar was grounded by using a knife mill (Grindomix GM 200, Retsch, Germany) for 10 s at 6000 rpm and then it was sieved at 600, 400 and 200 μm with certified sieve (Test Sieve, Retsch, Germany). Three different ranges of sugar size were obtained: <200 μm, 200 < μm < 400, 400 < μm < 600. For a better readability such ranges will be indicated through the text as particle size of sugar of 200, 400 and 600, respectively.

2.2. Experimental design

In the present study three strategies with three levels of variations were investigated and modulated with a Box-Behnken design (BBD) [19]. Specifically, sugar particle size of 200, 400 and 600 μm, mass fractions of vanillin of 0, 1 and 2%, and distribution of sugar in 1 (homogeneous), 3 and 5 layers (inhomogeneous samples) of different food formula were investigated. The number of experiments (N) required for the development of BBD was defined as $N = 2k(k\text{-}1) + C_0$, where k is the number of the independent variables ($k = 3$) and C_0 is the number of central points ($C_0 = 4$), for a total of 16 experiments. The experiments were repeated in triplicates. Table 1 reports the coded and real variables of the BBD.

2.3. Muffin preparation

Muffins were prepared by mixing eggs and sugar with a planetary kneader (model cooking chef, Kenwood Ltd. UK) for 3 min at maximum speed. For food formula with 'zero' sugar content only eggs were mixed, as shown in the proximate composition of food formula reported in Table 2. Then yogurt, sunflower oil and colorant (only in food formula with 'zero' sugar content) were added and mixed for 2 min. At the end, wheat flour, baking powder and vanillin (when planned based on experimental design) were included and mixed for 2 min at high speed. The dough was rest for about 30 min, then samples of 33 g of the batter were cooked in ordinary oven at 160 °C for 10 min. After baking, samples were cooled for about 60 min at room temperature until to be used for analysis. Only for sensory analysis, all samples were baked the day before, left to cool at room temperature for 60 min and packed in a polyethylene bags until to be served to consumers.

The choice of the ingredients and their mass fractions, reported in Table 2, were based on a commercial muffin-like product addressed for children, but with a reduced sugar content of about 30% in order to reach the claim 'with reduced sugar rate', based on the EU Regulation n. 1924/2006. On such food formula, vanillin was varied from 0 to 2% to the mass fraction of wheat flour, as per the experimental design. Indeed, for layered samples, the mean total sugar concentration was kept the same to the sample with homogeneous distribution of about 20.3%, but different layers were designed with different sugar content, as showed in Fig. 1(a, b, c). Also, food formula used for inhomogeneous distribution are reported in Table 2. Food formula with 'zero' sugar content was selected for samples with inhomogeneous distribution because, as demonstrated by Stieger [14], the more was the concentration gradient of sucrose among layers the more was the sweetness enhancement.

Table 1
Box-Behnken design for muffins at reduced sugar content. Coded and real values of independent variables used in this study are reported.

Run	Coded values			Real values		
	X_1	X_2	X_3	Sugar particle size (μm) [X_1]	Added vanillin (%) [X_2]	Stratification levels [X_3]
1	−1	0	+1	<200	1	5
2	+1	−1	0	600	0	3
3	−1	−1	0	200	0	3
4	+1	+1	0	600	2	3
5	−1	0	−1	200	1	1
6	+1	0	−1	600	1	1
7	−1	0	+1	200	1	5
8	+1	0	+1	600	1	5
9	0	−1	−1	400	0	1
10	0	+1	−1	400	2	1
11	0	−1	+1	400	0	5
12	0	+1	+1	400	2	5
13	0	0	0	400	1	3
14	0	0	0	400	1	3
15	0	0	0	400	1	3
16	0	0	0	400	1	3

Table 2
Food formula used for homogeneous distribution or 1 layer muffins (F1) and for muffins with inhomogeneous distribution or 3 and 5 layers samples (F2, F3 and F4).

Ingredients (g/100 g)	F1	F2	F3	F4
Wheat flour	31.2	39.2	27.2	25.9
Eggs	23.5	29.4	20.5	19.5
Sugar	**20.3**	**0**	**30.5**	**33.8**
Whole-milk yogurt	7.1	8.9	6.2	5.9
Sunflower oil	16.8	21.1	14.7	14.0
Baking powder	1.1	1.4	1.0	0.9

2.4. Physical analysis

2.4.1. Moisture content and water activity

Moisture content was measured gravimetrically as described in AOAC–925.10. Water activity was measured by using a dew-point system (AquaLab, Decagon Devices, US) previously calibrated with standard solutions. All analysis were measured in triplicates on each sample.

2.4.2. Weight loss

The weight loss after baking was computed as fractional decrease between the weight of the batters and the weight of the baked samples. Analyses were repeated on five samples.

2.4.3. Morphological properties

The main dimensional properties – maximum height (H_{max}), minimum height (H_{min}), diameter (D) - were measured on cooked muffin by using a universal Crafsman caliper, as described in Severini et al. [20]. At least 3 replicates were carried out for each muffin.

2.4.4. Colour parameters

The colour of samples was recorded by using a colour meter Mod. CR 400 (Minolta, Japan) and the CIE L*a*b* international scale parameters was used to express data. Independent measures of L*, a* and b* were randomly carried out on the surface of muffin performing at least 5 replicates for each sample.

2.4.5. Textural properties

Texture properties were measured with a TAX-T2 texture analyser (Stable Micro Systems, Surrey, UK) equipped with a 50 N load cell and using the experimental conditions defined by Severini et al. [20]. First, the muffins were crop to get a cylinder of 4 cm of diameter and were analyzed by applying a cross-head speed of 1 mm/s. The midsections of the samples were compressed for 50% of the total height by using a plate of diameter of 7.6 cm. After unloading and 5 s of break, a second compression was performed. From each test the following texture properties were measured: hardness (N), springiness (mm), cohesiveness and chewiness (N*mm).

All results were analyzed adopting the software EXPONENT version 2.0.6.0 (Stable Micro System, Surrey, UK). 5 samples for each condition were measured.

2.4.6. Microstructural properties

The cross-sectional X-ray images of the microstructure of muffin of 1304(x) x 1024(y) pixels and with a resolution of 28.5 μm were obtained by using a SkyScan 1174 micro-CT scanner (Brüker, Kontich, Belgium) in the following conditions: 50 kV, exposure time of 1200 ms, source current of 800 μm, averaging frame of 3; rotation step of 0.3°; total scanning time of 72 min.

The reconstructions of muffin were obtained by using Nrecon 1.6.2.0

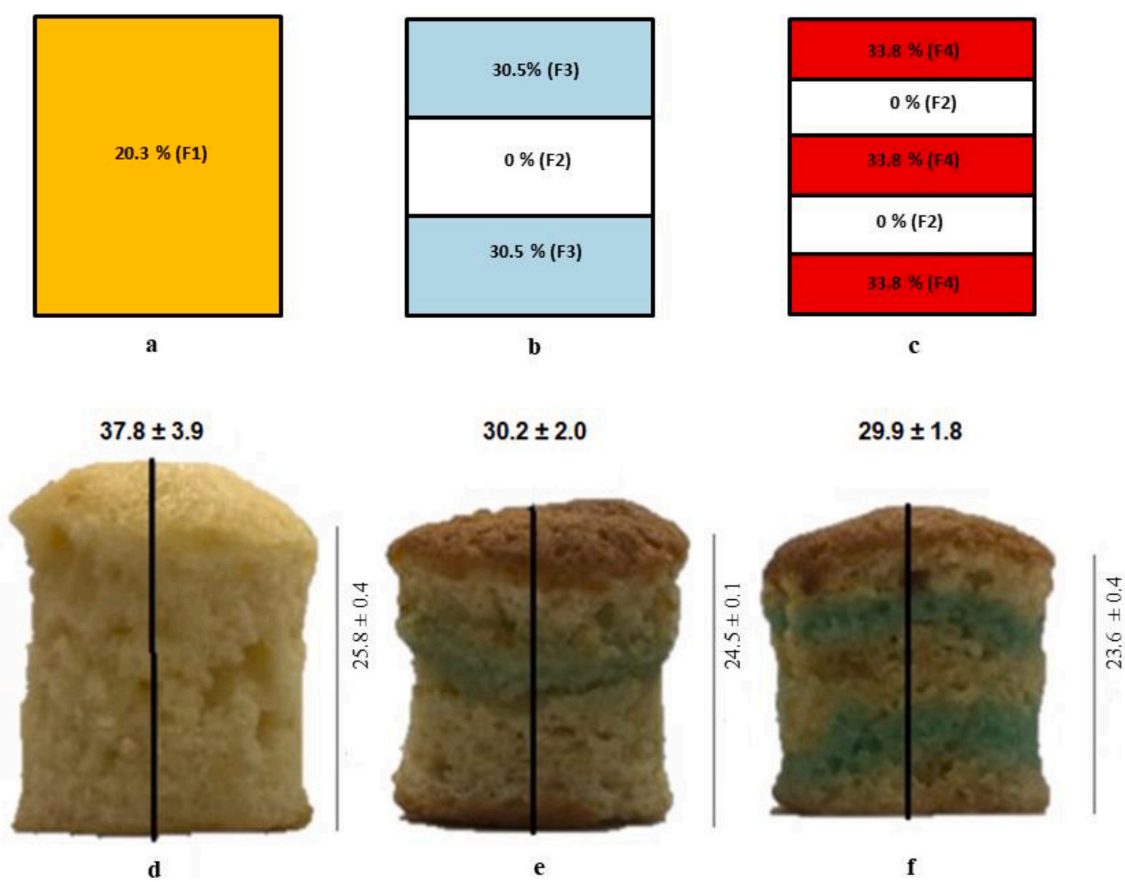

Fig. 1. (a, b, c) Structures of samples with sugar content of each layer and relative code of food formula used; (d, e, f) Representative photographic images of homogeneous and inhomogeneous muffins. Values of maximum (—) and minimum (—) heights (mm) are reported.

software (Bruker, Kontich, Belgium). Image processing consisted in the image thresholding, by applying a binary selection, with the aim to achieve the better separation between voids and solid structures. After that, despeckle function was used to reduce the noise of the image deleting solid elements (i.e. white pixels) having a size lower than 5 pixels. 2D and 3D analyses of the samples were performed by using CTAn 1.12.0.0 (Bruker microCT, Belgium). Porosity fraction was computed on a region of interest (ROI) fitting the entire diameter of the object, consisting of total cross-sectional images of $N = 900$. All measurements were performed on one representative sample for each structure.

2.5. Sweetness evaluation

Sweetness evaluation was carried out in Foggia, Italy, on a total of 46 children, aged 7–8 years old. Participants first rated the sweetness of three beverages of water and sugar at three different concentration (0–5 – 10%), randomly offered to children, based on a 5-point scale. After, all muffins were randomly evaluated for their sweetness on the same 5-point scale, where 1 = not sweet at all, and 5 = extremely sweet.

2.6. Statistical analysis

Experimental data were analyzed by using a polynomial model in order to define the effects of independent variables on the quality attributes of samples. The following polynomial model was used:

$$y = B_o + \sum B_i\, x_i + \sum B_{ii}\, x^2_{ii} + \sum B_{ij}\, x_{ij} \tag{1}$$

where B_0 is the initial value of the dependent variables, B_i, B_{ii}, B_{ij} are the regression coefficients, x_i indicates the linear effect of the independent variables, x^2_{ii} refers to the non-linear (quadratic) effect of the independent variables while x_{ij} refers to the linear and interactive effect of the independent variables. The goodness of fitting was evaluated by correlation coefficient (r), significance (p_{level}) and corresponding standard error (SE) of each regression coefficient estimated.

3. Results and discussion

3.1. Physical characteristics of muffins

The estimated effects of independent variables on the main physical characteristics of muffins are shown in Table 3. The level of stratification was the only significant variable for all analyzed quality parameters. Moisture content was affected by stratification levels through linear (3.65) and non-linear (2.93) effects ($p < 0.05$), resulting in average values ranged from 19.1% for homogeneous samples to >20.5% in both the stratified samples, with negligible differences between muffins with 3- and 5- layers (data not shown). It is useful to recall that stratified samples were obtained by interchanging – along the height of muffins - layers with no sugar (F2) with layers containing 30.5 g/100 g (F3) and 33.8 g/100 g (F4) of sugar, respectively for 3- and 5- layers samples. Being sugar highly hygroscopic, it creates several hydrogen bounds to water contributing in moisture retention [8,21] in F3 and F4 layers of the inhomogeneous samples. In addition, caramelization of crust, due to the high sugar content of the top and bottom layers in inhomogeneous muffins, contributes for moisture retention because the melting of sugars generated a physical barrier that limited water evaporation [8]. Contrarily water activity and weight loss were not affected by any independent variable (Table 3). This seems in contrast with results of moisture content but presumably the strong interaction of sugar with water leads to a decrease of the water activity in the layers rich in sugar, F3 and F4, while the lack of sugar in layers F2 caused a high water activity. Probably, these opposite effects, counterbalanced the variation of water activity inside the stratified samples [8] making negligible the effect on this parameter. Instead, for weight loss we want to note that the differences in moisture content among all samples were ≈ 1% with slight effects on the weight of muffins.

The main dimensions of muffins were significantly altered by stratification levels which showed estimated effects of −3.64, −7.14 and −4.09 respectively for the minimum height, maximum height and diameter (Table 3). A visual comparison of representative photographic images of samples suggests that homogeneous muffins definitively showed the greater structural expansion with an average maximum height of 37.8 ± 3.9 mm, while values of ≈ 30 mm were measured for both muffins with 3- and 5-layers (Fig. 1d, e, f).

We want to note that the layers without sugar – blue colour – are short and characterized by a reduced expansion. Such decreased expansion as well as the reduced dimension of products with low sugar content is also confirmed in several studies [22,23]. When sucrose content is low, the starch gelatinization and full development of protein network are favoured because more water is available for such reactions leading to high rigidity of the structure that hinders the expansion of pores under the action of CO_2 and water evaporation. So, products with low sugar content are generally less expanded and their volume/dimensions are shortened [13,24]. Moreover, the first step of muffin preparation is 'creaming' which consists of a high speed mixing of sugars and fats. However, lipids cannot dissolve sugar crystals which help to stabilize the air-fat foam interface enhancing structure and volume in cakes [25].

What is more, in baked goods it is expected a peak in the centre, the so-called 'dome-shape', due to the rising of the product that implemented during baking. It could be observed that in layered muffins this typical shape is less pronounced, as attested by the presence of slight differences between maximum and minimum heights. Other authors reported flatter surfaces in cakes obtained with inhomogeneous spatial distribution of sucrose [13].

Regarding colour parameters it is shown, once again, stratification

Table 3
Standardized estimated effects of independent variables and their interaction on some physical parameters of cooked muffins.

Independent variables	Estimated effects								
	Moisture content	Water activity	Minimum height	Maximum height	Diameter	Weight loss	L*	a*	b*
Sugar particle size (L)	1.28	−0.94	−0.77	−0.39	−0.31	−1.77	1.10	−0.28	0.51
Sugar particle size (Q)	1.25	0.85	0.71	0.12	0.06	1.55	1.39	−1.10	0.46
Added vanillin (L)	−1.49	−1.38	0.36	0.13	0.91	0.20	0.11	0.98	1.07
Added vanillin (Q)	0.60	1.48	1.16	0.03	1.20	−0.23	−0.08	0.85	0.11
Stratification levels (L)	3.65*	1.72	−3.64*	−7.14*	−4.09*	−1.19	−4.35*	5.41*	−4.28*
Stratification levels (Q)	2.93*	0.61	0.01	−4.49*	0.05	−1.89	−3.10*	4.33*	−2.47*
Sugar particle size *x* Added vanillin	1.27	1.89	−0.25	−0.03	−0.26	−0.72	−0.66	−0.84	−0.16
Sugar particle size *x* Stratification levels	−0.02	−1.24	0.02	−1.22	−0.13	0.13	0.33	0.08	−0.28
Added vanillin *x* Stratification levels	0.50	−0.45	−1.02	−0.53	−0.27	−1.38	−0.43	−0.25	−1.23

(L) linear effect; (Q) quadratic or non linear effect. L* is the colour parameter for lightness, a* for redness and b* for yellowness.
* Statistically significant at $p < 0.05$.

levels had a negative and both linear and non-linear effects on lightness (L*), with values of −4.35 and − 3.10 respectively as well as on yellowness (b*), with values of −4.28 and − 2.47. Conversely the independent variable had a positive linear (5.41) and non-linear (4.33) effect on red index (a*) (Table 3). These effects are linked to Maillard reaction and sugar caramelization, which contributed to the formation of brown compounds responsible of the decrement of lightness and yellow index and the increase of the red index [26]. It is important to underline that this effect arose in stratified samples where external layers contain higher amount of sugars (30.5% and 33.8%) while the homogeneous samples contain a weight fraction of sugar of 20.3%. Our data also well agree with Esteller et al. [27] who highlighted high level of brown compounds from Maillard reaction in products with high sugar content.

3.2. Textural properties of muffins

The effects of independent variables on textural properties of muffins are illustrated in Table 4. Stratification levels exhibited significant positive effect on all analysed textural parameters, except for Springiness, which was negatively influenced by inhomogeneous distribution, with estimated linear effect of −13.49 and non-linear effect of −7.21. Specifically, the estimated effect for Hardness, Cohesiveness and Chewiness were of 10.59, 14.14, 16.29, respectively. For muffins, as in all baked goods, leavening of dough and baking process allow the products to expand forming a sponge-like texture [24]. However, most of the studies that analysed textural properties in baked products with low sugar content found an increase in hardness. For instance, Martinez-Cervera et al. [28] measured a raise in hardness and a decrease of springiness for muffins obtained by replacing sucrose with different polyols. Dadali and Elmaci [13] attested that inhomogeneous distribution of sugar in cakes caused harder samples, even if for other textural parameters they didn't highlighted any significant effect.

A possible reason for the increase in hardness is the hygroscopicity of sugar. When sugar is removed from the dough, starch gelatinization and gluten hydration are significantly favoured and also they occur at a reduced temperature. Sure enough, these may cause the untimely hardening of the batters that limits the formation and expansion of gas bubbles in muffin during baking [29] increasing the hardness of the final products. Also, Cohesiveness and Chewiness, which are secondary texture parameters associated with difficulty of chewing the sample, followed the same trend of hardness. Stratified muffins resulted high in density and with lower number of gas cells which implies more time to recover the initial structure after first compression as well as a higher resistance to the second cycle of compression [26]. For the same reasons springiness, which is defined as 'how well a product physically springs back after it has been deformed', decreased in layered samples.

Furthermore, chewiness revealed an interactive positive effect between particle size of sugar and stratification levels of about 2.83 (Table 4). To better understand the interactive effect, in Fig. 2 is reported the surface response plot describing the effects of particle size of sugar (µm) and stratification levels on the chewiness of muffins. While for 1- layered samples any changes in particle size of sugar didn't affect the chewiness of muffin, for stratified samples the effect of particle size of sugar progressively increased. Specifically, for muffin with 5-layers, chewiness values varied from about 140 N*mm to about 200 N*mm, respectively for particle size of sugar of 200 and 600 µm.

Table 4
Standardized estimated effects of independent variables and their interaction on textural parameters of cooked muffins.

Independent variables	Estimated effects			
	Hardness	Springiness	Choesiveness	Chewiness
Sugar particle size (L)	1.19	1.17	−0.47	1.79
Sugar particle size (Q)	0.41	−1.53	0.69	−0.04
Added vanillin (L)	−0.01	1.34	−1.02	−0.47
Added vanillin (Q)	−1.55	0.49	0.83	−0.68
Stratification levels (L)	10.59*	−13.39*	14.14*	16.29*
Stratification levels (Q)	−3.33*	−7.21*	0.52	−5.92*
Sugar particle size *x* Added vanillin	0.59	−0.84	−1.86	−0.85
Sugar particle size *x* Stratification levels	1.77	−1.42	1.73	2.83*
Added vanillin *x* Stratification levels	0.39	−0.93	−1.33	−0.66

(L) linear effect; (Q) quadratic or non linear effect.
* Statistically significant at $p < 0.05$.

3.3. Microstructural characteristics of muffins

In order to study the microstructure of muffin, Fig. 3 shows the estimated effects of independent variables on porosity fraction. The particle size of sugar showed a positive and non-linear effect of 3.06, while stratification levels and added vanillin exhibited a negative effect on total porosity, correspondingly to −2.96 (non-linear) and − 2.46 (linear).

First, we want to analyze the effect of sugar stratification. As previously reported, sugar plays a critical role on the expansion of bakery product with a weak development of gas cells (i.e. the pores) in samples at reduced amount of sugar [11]. In addition, the creaming phase strengthens the stability of air-fat-foam because sugars remain undiluted in fats generating a more homogeneous morphological properties of pores (i.e. shape and dimension) within the structure of muffin samples, as evident from the cross-sectional images of Fig. 4. Furthermore, the images of not-layered muffin (F1) and from region at high (F3 and F4) and zero sugar content (F2) for both the inhomogeneous samples indicated a higher porosity in region with high sugar content according to the abovementioned phenomena. Particularly, porosity fractions of 55.3% has been measured for zero-sugar layers, F2, while values of 65.0% and 72.5% were measured for regions F3 and F4. Finally, the no-stratified samples, F1, exhibited a porosity fraction of 68.2%. These data prove the great effect of sugar on the higher expansion of dough during cooking [26,30]. However, when we analyze the entire structure of muffin rather than the separated regions, the effect on porosity fraction were slight and more complex. For instance, the global porosity fraction for 3-layers and 5-layers muffin showed average values of 58.4% and 65.6%. One reason of such differences could be the partial redistribution of the regions with zero and high sugar occurring during baking under the action of the expansion of underlying layers. This effect could be more pronounced in the sample of 5-layers because it consists of layers without sugar, F2, of a weight of only 6.6 g rather than the 11 g inside the 3-layers muffin. Indeed, while porosity fraction of F2 in 3-layer samples was of 51.8%, the same food formula with zero sugar showed a porosity fraction of 58.7% in 5-layers muffins, suggesting a greater

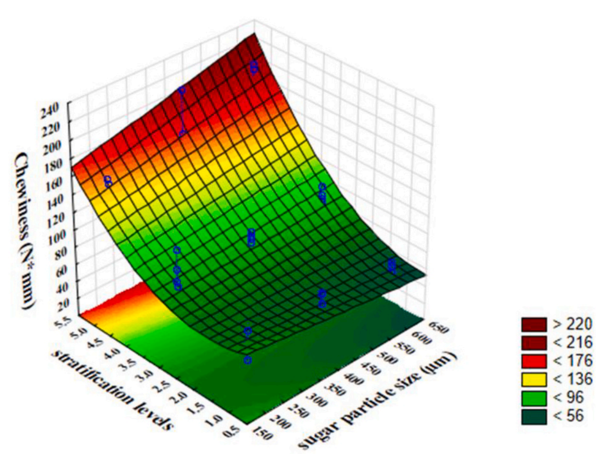

Fig. 2. Surface response plot describing the effects of sugar particle size (µm) and stratification levels on the Chewiness of muffins.

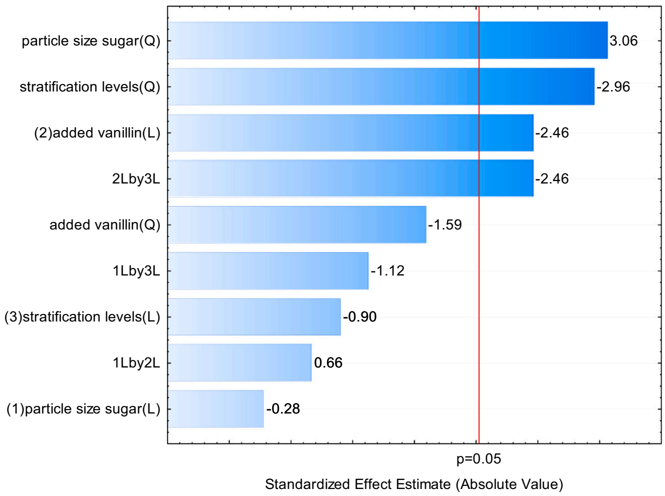

Fig. 3. Estimated Effects of independent variables on porosity of muffins.

redistribution for 5-layers samples. This hypothesis is also suggested by the cross-sectional images of Fig. 4 for the regions at zero sugar content in which it is possible to observe two main regions at high and low porosity fractions.

Next, regarding the non-linear and positive effect of sugar particle size, the differences in porosity fraction could be attributed to cohesive properties of sugar which are dependent on size. Dozan et al. [31] founded that particle size below 200 µm and higher that 610 µm showed sticky and cohesive properties, which probably reflects the lower porosity fraction exhibited in our study.

A more intricate behaviour was observed for vanillin addition which showed an inverse relationship with porosity fraction of muffin (Fig. 3). Also, a negative interaction between vanillin and stratification levels was observed. In 5-layers muffin by increasing added vanillin from 0 to 2% the porosity fraction drastically decreased from about 80% to 60%, while in homogeneous samples an opposite effect of these two independent variables was highlighted (Fig. 5).

This is in disagreement with the majority of literature in which any effect for vanillin or other aroma compounds on the structure of baked product was not reported [30]. Further experiments should be performed to precisely separate the effect of each ingredients and the stratification approach on the overall microstructure properties of samples.

3.4. Hedonic evaluation of sweetness of muffins

Firstly we evaluated the capacity of children to discriminate among beverages with different sugar concentration (from 0% to 15%) and recruiting only 33 children on a total of 45 participants for the hedonic test on muffin samples.

The effects of independent variables on sweetness perception of muffins are reported in Fig. 6. Firstly, added vanillin showed a non-linear effect of 2.44. It is extensively reported that although aroma and taste are perceived by separate physiological routes, the intensity of taste may be modified by aroma perception – and vice versa - when these two stimuli interact with congruency, as for the association of fruitiness with sweetness, ‘cheese’ notes with saltiness, etc. [32–34]. Results of this and other experiments affirm the potential of vanillin to be used as ‘taste enhancer’ [16,35–37]. Nonetheless, all the studies that investigated these effects also stressed the importance of the food matrix where the enhancer is added and the quantities used because cross-modal aroma–taste interactions have been reported to be aroma- and product-specific [15]. Actually, these interactions are characterized by complex physico-chemical, physiological and psychological

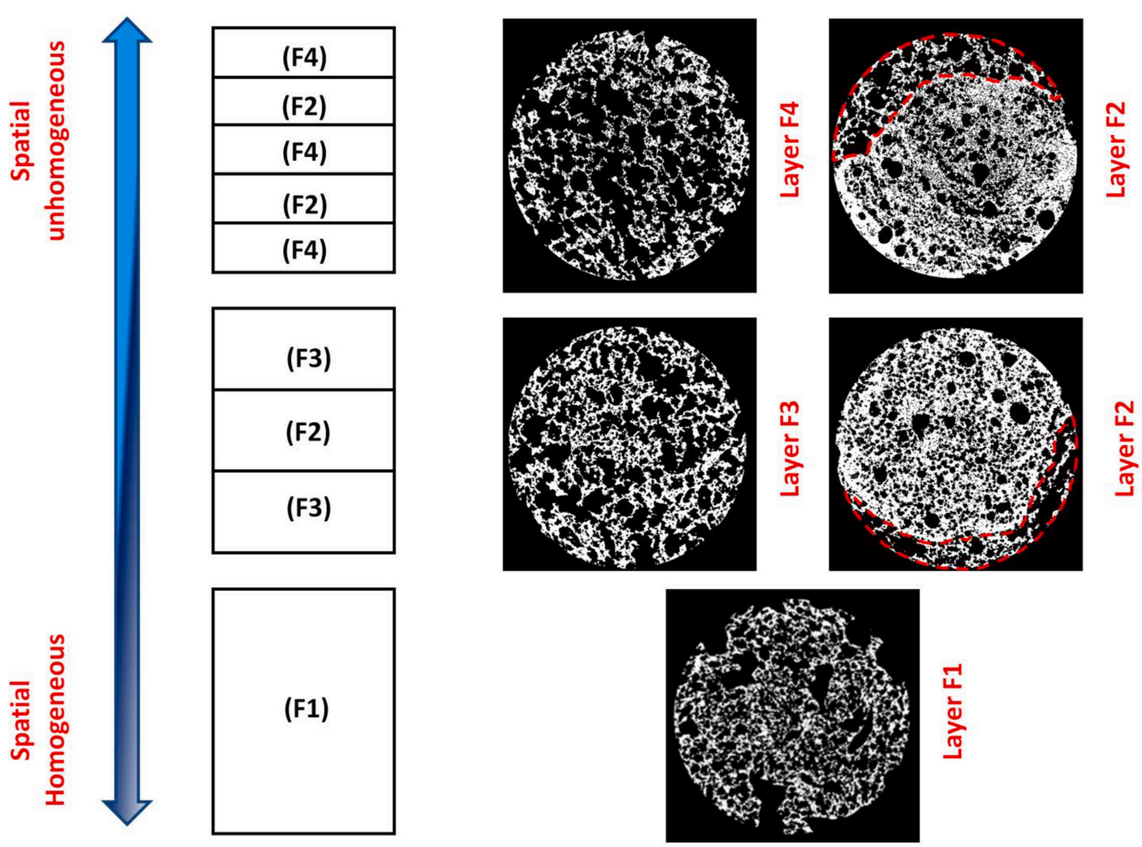

Fig. 4. Representative microCT images of layers at different sugar content (F1: 20.3%, F2: 0%, F3: 30.5, F4: 33.8%) of homogeneous and inhomogeneous muffins.

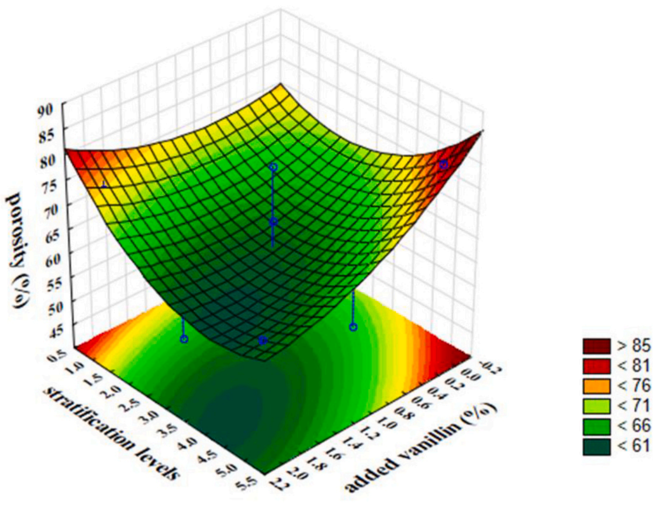

Fig. 5. Surface response plot describing the effects of stratification levels and added vanillin (%) on the porosity fraction (%) of muffins.

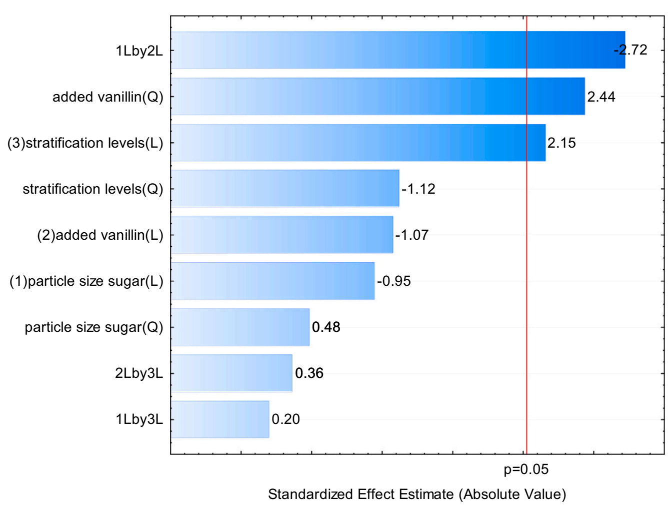

Fig. 6. Estimated Effects of independent variables on Sweetness perception on muffins.

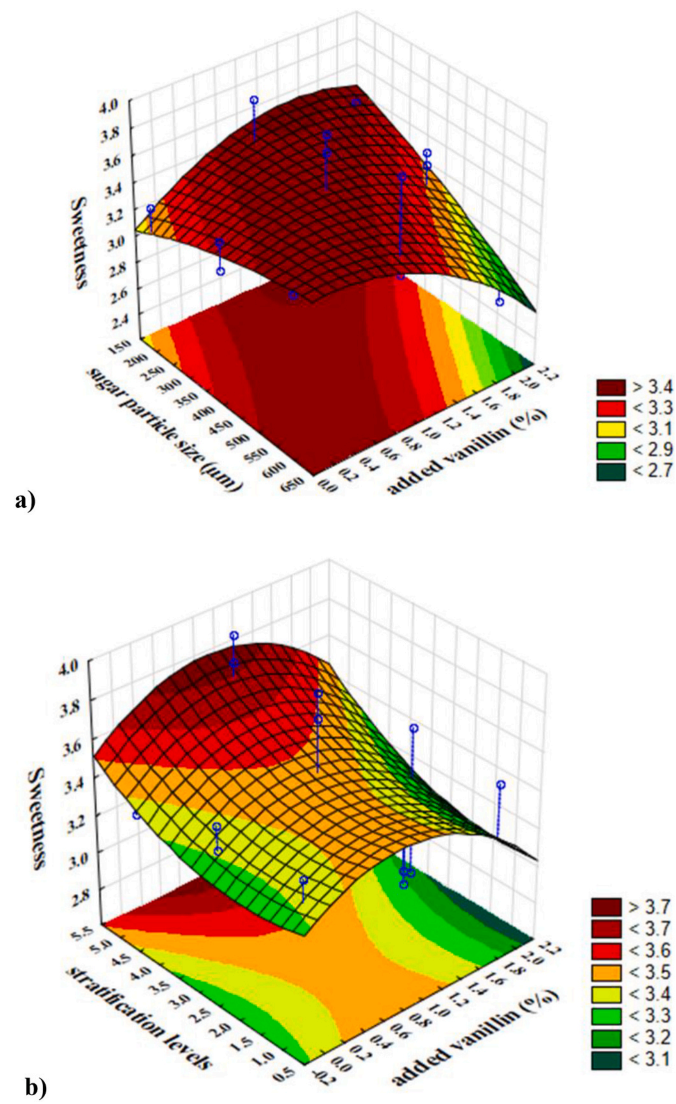

Fig. 7. Surface response plot describing (a) the effects of sugar particle size (µm) and added vanillin (%) and (b) the effects of stratification levels and added vanillin (%) on the Sweetness perception of muffins.

mechanisms leading to divergent or unexpected results that need further investigation. As a matter of fact, in our study it is also highlighted an interactive effect of vanillin and sugar particle size of −2.72 (Fig. 6). As visible in Fig. 7a, with sugar particle size dimensions of 600 µm, the increase of the amount of vanillin reduced the sweetness perception, but this was not observed for lower particle size dimensions of sugar where an opposite effect was revealed. Probably, this is a result of a change in food matrix which impacts on diffusion of volatiles and, also, their release inducing changes in sweetness intensity [14,33].

Moreover, stratification levels exhibited a linear effect of 2.15 on sweetness perception. It was observed an increase of sweetness from ~3.3 to ~3.6, respectively for homogenous muffins and for 5-layers muffins with no added vanillin even if with 1% of vanillin in 5-layers muffins it was reached the highest sweetness perception (Fig. 7b). Also, other studies demonstrated as the inhomogeneous distribution of sucrose increased sweetness perception in comparison to samples with homogeneous distribution [13,14,18,38]. This was probably due to the asynchronous discontinuous stimulation of the taste receptors during break down of foods in the mouth. It was demonstrated that pulsation of taste stimuli, as in the case of inhomogeneous distribution, would be perceived more intense compared to an average–sized continuous stimulus [13,18]. In addition, when eating our stratified samples, the receptors initially met external layers of muffin with high sugar content (Fig. 1), resulting in the higher sweetness perception.

4. Conclusions

In this contribution the results of adopting a complex strategy that involves the usage of inhomogeneous spatial distribution of sugar, multisensory interaction and different particle size of sugar, were presented. The proposed methodology was effective in improving the perception of sweetness of innovative muffins designed for children. The inhomogeneous distribution of layers at high sugar content (30.5% or 33.8%) interchanged with layers at zero sugar were perceived as more sweet than homogeneous samples. In addition, we found that the usage of vanillin at 1% produced the sweetest muffin samples confirming its potential as taste enhancer, especially in synergistic effect with sugar particle size less than 400 µm. On the other hand, the innovative muffins exhibited a lower height and an increased hardness due to the limited formation of gas bubbles and the high density in the layers with zero sugar where the starch gelatinization and gluten formation could be favoured. Our results prove as the adopted multiple and integrated technological approaches, never combined before, would allow the development of muffins at low sugar content but sensorial perceived as sweet, highly appreciated, and capable of tackling the challenge of reducing the daily sugar intake of children. Further experiments will allow to extend this approach to other cereal-based products designed for different consumer's categories and specific needs.

Founding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

None.

References

[1] World Health Organization, Obesity and Overweight. https://www.who.int/gho/ncd/risk_factors/overweight_adolescents_text/en/, 2017 (accessed 15 June 2020).
[2] M. Lima, G. Ares, R. Deliza, Comparison of two sugar reduction strategies with children: case study with grape nectars, Food Qual. Prefer. 71 (2019) 163–167, https://doi.org/10.1016/j.foodqual.2018.07.002.
[3] X. Luo, J. Arcot, T. Gill, J.C.Y. Louie, A.A. Rangan, Review of food reformulation of baked products to reduce added sugar intake, Trends Food Sci. Tech. 86 (2019) 412–425, https://doi.org/10.1016/j.tifs.2019.02.051.
[4] P.J. Moynihan, S.A. Kelly, Effect on caries of restricting sugars intake systematic review to inform WHO guidelines, J. Dent. Res. 93 (2014) 8–18, https://doi.org/10.1177/0022034513508954.
[5] A.M. Richardson, A.A. Tyuftin, K.N. Kilcawley, E. Gallagher, M.G.O. Sullivan, J. P. Kerry, The impact of sugar particle size manipulation on the physical and sensory properties of chocolate brownies, LWT- Food Sci. Technol. 95 (2018) 51–57, https://doi.org/10.1016/j.lwt.2018.04.038.
[6] European Food Safety Authority, Scientific Opinion on Dietary Reference Values for Carbohydrates and Dietary Fibre. https://www.efsa.europa.eu/en/efsajournal/pub/1462, 2010 (accessed 9 May 2020).
[7] World Health Organization, Guideline: Sugars Intake for Adults and Children. http://www.who.int/nutrition/publications/guidelines/sugars_intake/en/, 2015 (accessed 22 April 2020).
[8] A.W. Sahin, E. Zannini, A. Coffey, E.K. Arendt, Sugar reduction in bakery products: current strategies and sourdough technology as a potential novel approach, Food Res. Int. 126 (2019) 108583, https://doi.org/10.1016/j.foodres.2019.108583.
[9] T.J.L. van Rompay, S. Groothedde, The taste of touch: enhancing saltiness impressions through surface texture design, Food Qual. Prefer. 73 (2019) 248–254, https://doi.org/10.1016/j.foodqual.2018.11.003.
[10] L. Milner, J.P. Kerry, M.G. O'Sullivan, E. Gallagher, Physical, textural and sensory characteristics of reduced sucrose cakes, incorporated with clean-label sugar replacing alternative ingredients, Innov. Food Sci. Emerg. Technol. 59 (2020) 102235, https://doi.org/10.1016/j.ifset.2019.102235.
[11] R. Di Monaco, N.A. Miele, E.K. Cabisidan, S. Cavella, Strategies to reduce sugars in food, Curr. Opin. Food Sci. 19 (2018) 92–97, https://doi.org/10.1016/j.cofs.2018.03.008.
[12] S. Zorn, F. Alcaire, L. Vidal, A. Giménez, G. Ares, Application of multiple-sip temporal dominance of sensations to the evaluation of sweeteners, Food Qual. Prefer. 36 (2014) 135–143, https://doi.org/10.1016/j.foodqual.2014.04.003.
[13] C. Dadalı, Y. Elmacı, Reduction of sucrose by inhomogeneous distribution in cake formulation, Food Measur. 13 (2019) 2563–2570, https://doi.org/10.1007/s11694-019-00176-7.
[14] M. Stieger, Texture-taste interactions: Enhancement of taste intensity by structural modifications of the food matrix, Procedia Food Sci. 1 (2011) 521–527, https://doi.org/10.1016/j.profoo.2011.09.079.
[15] F. Alcaire, L. Antúnez, L. Vidal, A. Giménez, G. Ares, Aroma-related cross-modal interactions for sugar reduction in milk desserts: Influence on consumer perception, Food Res. Int. 97 (2017) 45–50, https://doi.org/10.1016/j.foodres.2017.02.019.
[16] C. Tournier, C. Sulmont-Rossé, E. Sémon, A. Vignon, S. Issanchou, E. Guichard, A study on texture–taste–aroma interactions: physico-chemical and cognitive mechanisms, Int. Dairy J. 19 (2009) 450–458, https://doi.org/10.1016/j.idairyj.2009.01.003.
[17] M. Stieger, F. van de Velde, Microstructure, texture and oral processing: New ways to reduce sugar and salt in foods, Curr. Opin. Colloid Interface Sci. 18 (4) (2013) 334–348, https://doi.org/10.1016/j.cocis.2013.04.007.
[18] K. Holm, K. Wendin, A.M. Hermansson, Sweetness and texture perceptions in structured gelatin gels with embedded sugar rich domains, Food Hydrocoll. 23 (8) (2009) 2388–2393, https://doi.org/10.1016/j.foodhyd.2009.06.016.
[19] G.E.P. Box, W.G. Hunter, J.S. Hunter, Statistics for experimenters, Wiley New York, 1978.
[20] C. Severini, R. Caporizzi, A.G. Fiore, I. Ricci, O.M. Onur, A. Derossi, Reuse of spent espresso coffee as sustainable source of fibre and antioxidants. A map on functional, microstructure and sensory effects of novel enriched muffins, LWT-Food Sci. Technol. 119 (2020) 108877, https://doi.org/10.1016/j.lwt.2019.108877.
[21] S. Struck, D. Jaros, C.S. Brennan, H. Rohm, Sugar replacement in sweetened bakery goods, Int. J. Food Sci. Technol. 49 (2014) 1963–1976, https://doi.org/10.1111/ijfs.12617.
[22] G. Manisha, C. Soumya, D. Indrani, Studies on interaction between stevioside, liquid sorbitol, hydrocolloids and emulsifiers for replacement of sugar in cakes, Food Hydrocoll. 29 (2) (2012) 363–373, https://doi.org/10.1016/j.foodhyd.2012.04.011.
[23] F. Ronda, M. Gómez, C.A. Blanco, P.A. Caballero, Effects of polyols and nondigestible oligosaccharides on the quality of sugar-free sponge cakes, Food Chem. 90 (4) (2005) 549–555, https://doi.org/10.1016/j.foodchem.2004.05.023.
[24] R.A. Clemens, J.M. Jones, M. Kern, S.Y. Lee, E.J. Mayhew, J.L. Slavin, S. Zivanovic, Functionality of Sugars in Foods and Health, Compr. Rev. Food Sci. F. 15 (2016) 433–470, https://doi.org/10.1111/1541-4337.12194.
[25] E. Grewe, The emulsion-foam produced by agitating butter, sugar and egg: a method for testing the stability of the emulsion and the effect of the conditioning temperature of the fat, Cereal Chem. 14 (1937), 8020–18.
[26] S. Martínez-Cervera, T. Sanz, A. Salvador, S.M. Fiszman, Rheological, textural and sensorial properties of low-sucrose muffins reformulated with sucralose/polydextrose, LWT Food Sci. Technol. 45 (2) (2012) 213–220, https://doi.org/10.1016/j.lwt.2011.08.001.
[27] M.S. Esteller, A.C. Orlandi de Lima, S.C. da Silva Lannes, Color measurement in hamburger buns with fat and sugar replacers, LWT Food Sci. Technol. 39 (2) (2006) 184–187, https://doi.org/10.1016/j.lwt.2004.12.012.
[28] S. Martinez-Cervera, A. Salvador, T. Sanz, Comparison of different polyols as total sucrose replacers in muffins: thermal, rheological, texture and acceptability properties, Food Hydrocoll. 35 (2014) 1–8, https://doi.org/10.1016/j.foodhyd.2013.07.016.
[29] S. Karp, J. Wyrwisz, M. Kurek, A. Wierzbicka, Physical properties of muffins sweetened with steviol glycosides as the sucrose replacement, Food Sci. Biotechnol. 25 (2016) 1591–1596, https://doi.org/10.1007/s10068-016-0245-x.
[30] J. Gao, H. Fezhong, G. Xinbo, Z. Xian, L.S. Mason, A.M. Brennan, S.C. Brennan, Image analysis of the sugar-reduced muffin formulated with Stevianna® or inulin as a sugar replacer, Grain Oil Sci. Technol. 1 (2) (2018) 63–71, https://doi.org/10.3724/SP.J.1447.GOST.2018.18043.
[31] T. Dozan, M. Benkovic, I. Bauman, Sucrose particle size reduction – Determination of critical particle diameters causing flowability difficulties, J. Hyg. Eng. Des. 8 (2014) 3–10, 664–492.2:547.918.
[32] A.C. Noble, Taste–aroma interactions, Trends Food Sci. Technol. 7 (1996) 439–443, https://doi.org/10.1016/S0924-2244(96)10044-3.
[33] P. Poinot, G. Arvisenet, J. Ledauphin, J.L. Gaillard, C. Prost, How can aroma–related cross–modal interactions be analysed? A review of current methodologies, Food Qual, Pref 28 (1) (2013) 304–316, https://doi.org/10.1016/j.foodqual.2012.10.007.
[34] R.J. Stevenson, J. Prescott, R.A. Boakes, Confusing tastes and smells: how odours can influence the perception of sweet and sour tastes, Chem. Senses 24 (1999) 627–635, https://doi.org/10.1093/chemse/24.6.627.
[35] R.A. Boakes, H. Hemberger, Odour-modulation of taste ratings by chefs, Food Qual. Prefer. 25 (2012) 81–86, https://doi.org/10.1016/j.foodqual.2012.01.006.
[36] K.M.M. Burseg, S. Camacho, J. Knoop, J.H.F. Bult, Sweet taste intensity is enhanced by temporal fluctuation of aroma and taste, and depends on phase shift, Physiol. Behav. 101 (2010) 726–730, https://doi.org/10.1016/j.physbeh.2010.08.014.
[37] D. Oliveira, L. Antúnez, A. Giménez, J.C. Castura, R. Deliza, G. Ares, Sugar reduction in probiotic chocolate-flavored milk: impact on dynamic sensory profile and liking, Food Res. Int. 75 (2015) 148–156, https://doi.org/10.1016/j.foodres.2015.05.050.
[38] A.C. Mosca, F. van de Velde, J.H.F. Bult, M.A.J.S. van Boekel, M. Stieger, Effect of gel texture and sucrose spatial distribution on sweetness perception, LWT Food Sci. Technol. 46 (1) (2012) 183–188, https://doi.org/10.1016/j.lwt.2011.10.009.