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A study on optimizing functional oats and quinoa cookies: the role of fiber in enhancing texture, taste, and sensory acceptance of Rebaudioside A–sweetened formulation

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Abstract

Background: Since obesity, diabetes, and celiac disease are becoming global health issues, interest in low-calorie and gluten-free food consumption has increased over time. Sugar alternatives, such as Rebaudioside-A, have gained attention due to their health benefits and natural origins. In this study, we investigated the effects of Rebaudioside-A as a sugar substitute and inulin as a functional ingredient in gluten-free oat and quinoa cookies.

Objective: This study aimed to develop and optimize gluten-free, dairy-free, and sugar-free functional cookies formulated from oats and quinoa. Rebaudioside-A was used as a complete substitute for traditional sugar. As an alternative, a dietary fiber source, inulin, was incorporated with three primary objectives: enhancing the product's sensory acceptability and nutritional value and improving its binding properties to ensure structural integrity.

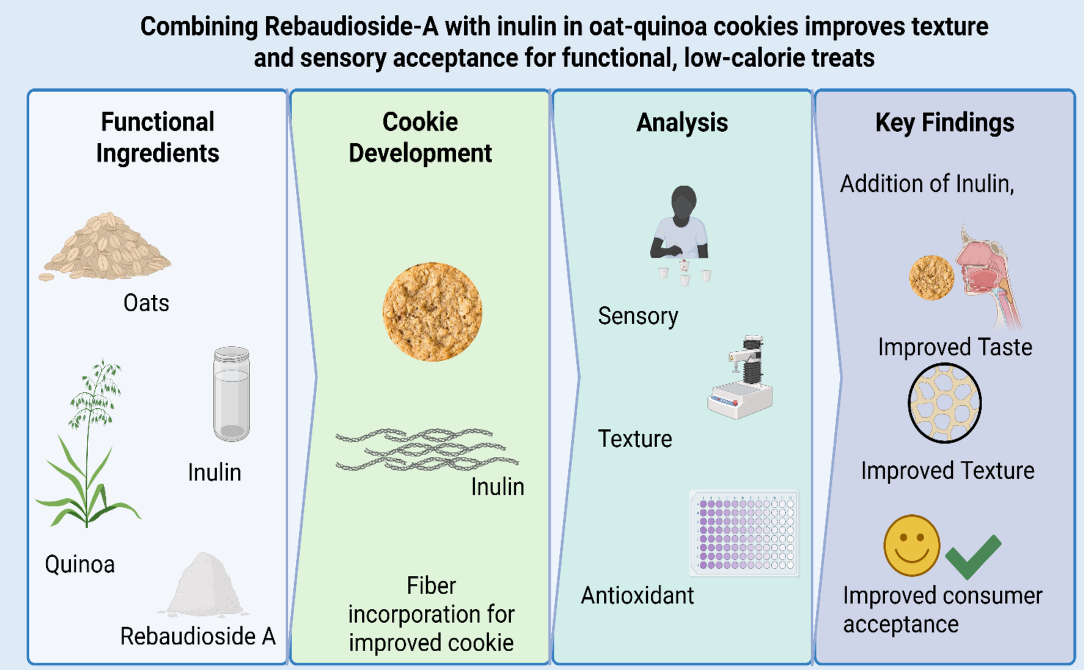
Methods: Oats and quinoa-based gluten-free cookies were formulated in three variations: sugar-based (SuC, control), Rebaudioside-A-based (StC), and Rebaudioside-A and Inulin-based (InStC). Water activity and texture analysis were performed on the same day of baking and after 5 days. Sensory analysis (n=103) was carried out following ethical approval.

Results: Sensory evaluation revealed that InStC had improved acceptability compared with StC alone due to the inclusion of inulin, with no difference in odor or color. Based on the sensory study results, there was no perceived difference between odor and color for the three formulations. Suc and InStC showed the same water activity and physical texture analysis results, and the texture sensory analysis also found the two products to be not different.

Conclusion: This study demonstrates that replacing sugar with Rebaudioside-A and incorporating inulin in gluten-free cookies is a novel and viable approach for developing functional, low-calorie baked goods. While Rebaudioside-A alone posed challenges in terms of aftertaste acceptability, adding inulin improved the sensory profile in terms of taste and texture.

Keywords: Non-caloric sweeteners, Inulin, Dairy-free, Gluten-free

Graphical Abstract: Combining Rebaudioside-A with inulin in oat-quinoa cookies improves texture and sensory acceptance for functional, low-calorie treats.



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INTRODUCTION

As global rates of obesity, diabetes, and celiac disease continue to escalate, particularly among children and adults, there is growing interest in the development and consumption of reduced-calorie and gluten-free food products. This has led to increased attention on the role of sweeteners and gluten-free ingredients as viable functional additives in food manufacturing [1-2]. According to the World Health Organization (WHO), overweight and obesity currently affect a significant portion of the European population, with approximately 60% of adults and one in three children impacted. Elevated body mass index (BMI) is recognized as a key risk factor for numerous non-communicable diseases, including cardiovascular conditions, various forms of cancer, and the number of people who have celiac disease is increasing [3-4]. While the development of obesity is influenced by multiple factors, excessive intake of high-sugar foods and beverages remains a primary contributor [5]. In response, the food industry is increasingly focused on innovating low-calorie, reduced-sugar, and gluten-free food products aimed at preventing obesity and associated metabolic disorders [6]. Ultra-processed foods, characterized by their high caloric content and low nutritional value, typically contain excessive amounts of added sugars, fats, and salts, while being low in protein [7]. Examples of such products include sugar-sweetened beverages, desserts, ice cream, chocolates, salty snacks, frozen meals, processed meats, and fast-food items such as hamburgers. Among popular processed foods, cookies remain a widely consumed snack, appreciated for their sensory appeal, affordability, and nutritional versatility depending on their composition.

Stevia (*Stevia rebaudiana* Bertoni*),* a perennial herb belonging to the Compositae (Asteraceae) family, was originally cultivated in South America and is now widely grown across continents, including Asia, Europe, and North America. Among approximately 150 known species within the Stevia genus, *Stevia rebaudiana* is the only species recognized for its naturally sweet properties [8]. The primary sweet-tasting compound found in this plant is Rebaudioside-A (Reb-A), a member of the steviol glycosides group [9]. Some steviol glycosides, such as Rebaudioside-A, have weaker off-flavors than stevioside; therefore, this variant is a candidate for improved taste profiles. As a 100% plant-derived, non-toxic sweetener, Stevia offers both commercial appeal and therapeutic benefits. It delivers intense sweetness with minimal calories and is increasingly favored for its functional properties in food production. Notably, Reb-A is estimated to be 200–300 times sweeter than sucrose. Yet it provides negligible energy and does not affect blood glucose levels, making it particularly suitable for diabetic and calorie-conscious diets [10-12]. These properties have facilitated their integration into various food categories, including dairy, baked goods, beverages, and jellies. Its use is primarily driven by the growing demand for low-calorie food options that offer health benefits without compromising taste or quality. Stevia and its components have been widely investigated as natural sugar substitutes in various food products. In reduced-calorie jams, for instance, apple jam formulated solely with stevia retained a favorable taste and aroma. However, its texture and appearance were altered, indicating the need for improving the physical properties of sugar-free products [13]. Another study demonstrated Reb-A as a promising substitute for sugar in sweetened beverages. In baked goods, sugar-free biscuits made from wheat, ragi, stevia, and gluten-free cookies formulated with almond flour and stevia showed higher sensory acceptance. However, cookies made with stevia were rated lower in preference due to a strong aftertaste, highlighting the need to optimize flavors to enhance consumer acceptance [14]. In addition to sweeteners, interest has grown in incorporating nutrient-rich grains such as quinoa into functional food products. Quinoa is considered a superfood due to its exceptional nutritional profile, which includes over 37% essential amino acids, 16–18% protein, and an abundance of vitamins, minerals, and unsaturated fatty acids such as alpha-linolenic and linoleic acids. It also contains amino acids such as cysteine, lysine, and methionine, which contribute to its high biological value [15]. Quinoa has been a dietary staple for centuries and remains highly valued for its rich nutrient content. Oats, another highly regarded grain, are rich in both protein and lipids, particularly linoleic acids, which constitute up to 45% of the lipid content in raw oats. Oats are well known for their pharmacological properties, including anti-inflammatory, antidiabetic, and immunomodulatory effects. They also provide a rich source of soluble fiber, particularly beta-glucans, making them a valuable addition to both gluten-free and standard diets [16].

The present study aims to develop and optimize functional cookies using a combination of oats

and quinoa as flour bases, and sweetened with Reb-A. The cookies will be evaluated for texture, flavor, and sensory appeal compared to conventional sugar-based and Reb-A-only formulations. This approach aims to address growing public health concerns, such as obesity, diabetes, and gluten intolerance, while enhancing the overall sensory quality of Reb-A-based bakery products.

MATERIALS AND METHODS

Product Development and Formulation

Ingredients: All raw materials required for cookie development were sourced from local markets in Limerick, Ireland. Ingredients included oats (John McCambridge Irish Gluten-free Oats), quinoa (wholefoods), sugar (Caster sugar), sunflower oil (pure sunflower oil), baking powder (Dunnes Stores), and salt (Saxa salt) were bought from Dunnes Stores, Ireland. Inulin (Holland and Barrett) used as a functional additive was procured from Holland & Barrett, Limerick, Ireland, and Rebaudioside-A (98% pure) was purchased online from Koro company (Stevia 2024).

Equipment: Cookie production was carried out using standard baking tools and equipment. A modular electric deck oven- Type: PPC-M (MECH-MASZ Szczecinski, Poland), was used for baking.

Experimental design and formation of cookies: Three cookie formulations were developed using oat and quinoa flour as base ingredients: (1) sugar-based control (SuC), (2) Reb-A-sweetened (StC), and (3) Reb-A combined with inulin (InStC). SuC served as the experimental control.

To prepare the different cookie formulations, quinoa and oat flours were finely ground, sieved (mesh Size 1.5mm), and combined with specific ingredients as per each recipe (Supplementary Table S1). For SuC, granulated sugar, Vanilla Essence, sunflower oil, baking powder, salt, and water were added, and the dough was kneaded, rolled to 0.5-inch thickness, cut, and baked in a preheated oven at 110 °C (bottom) and 210 °C (top) for 10 minutes. InStC used the same flour preparation, but with sunflower oil, baking powder, Vanilla Essence, salt, Rebaudioside-A, inulin, and water, following identical shaping and baking conditions, but for 15 minutes to ensure even texture. For the StC, the process was similar, with Reb-A as the sweetener and precise amounts of sunflower oil, baking powder, Vanilla Essence, salt, and water. These ingredients were also baked at the same temperature for 15 minutes to achieve the desired sensory quality.

Sensory Analysis: This study was conducted in the Food Grade laboratory of the Bernal Institute, University of Limerick, Ireland. Ethical permission was obtained from the University of Limerick Ethics Committee before initiating the sensory evaluation phase (application number: 2023_06_09_S&E). Participants provided written consent after receiving information about the study objectives, approaches, and protocols.

Cookies were prepared, and coded samples (SuC vs. StC, SuC vs. InStC) were distributed for blind, pairwise testing [17]. Using a 9-point hedonic scale, participants rated flavor, texture, visual appeal, odor, aftertaste, sweetness, and overall impression.

The acceptability index (AI) was calculated to assess the overall acceptability of each parameter for each beverage using the following formula: AI(%)=A x 100/B, where A=mean grade (obtained from the product), B=maximum grade (given to the product) [18].

Shelf-life Analysis: Cookies were prepared and stored in airtight plastic bags to conduct a shelf-life study. Physicochemical analyses were performed on samples collected on day 1 (the day of preparation) and day 5 (five days post-preparation) to assess changes in quality parameters during storage. This approach enabled the evaluation of the impact of storage duration on the cookies' physicochemical properties.

Physicochemical Evaluation:

Chemicals: 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical, 2,4,6-Tris(2-pyridyl)-s-triazine (TPTZ), gallic acid, and ascorbic acid were sourced from Sigma-Aldrich-Merck (Darmstadt, Germany). Hydrochloric acid (HCl) was obtained from Fluka (Milwaukee, WI, USA). Folin-Ciocalteu's phenol reagent, methanol, and ferric chloride hexahydrate were acquired from Merck KGaA (Darmstadt, Germany). Potassium chloride, glacial acetic acid, sodium carbonate, and sodium acetate were purchased from Scientific Laboratory Supplies (Dublin, Ireland).

Instrumental Texture Profile Analysis: The texture of cookies plays a significant role in enhancing their overall flavor and appeal. A high fiber content in cookies can contribute to a denser, crunchier texture by absorbing water and strengthening the overall structure of the cookie dough. One of the key aspects of a cookie's texture is its hardness, which is measured by the amount of force required to break it [19]. Texture Analyzer Stable Microsystems TA.XT2 equipment was used to measure the texture analysis of the developed cookies. A standard protocol was followed to measure the firmness (Fmax (N)) of the cookies. A 5 kg load cell, featuring a 10 cm diameter probe and a 5 cm length, was used for the measurements. Five tests were performed for each formulation.

Water activity: The "Aqua lab" (Series 3) water activity meter (Decagon Devices Inc., Pullman, Washington, USA) was used to evaluate the water activity of the developed cookies. Analysis was performed as per the equipment instructions in triplicate.

Antioxidant analysis: The antioxidant properties of the formulated cookies were evaluated through three complementary assays.

Sample Preparation: Before conducting antioxidant assays, 5 g samples were weighed into test tubes, mixed with 5 mL methanol, centrifuged (30 min), and supernatants collected for analysis. All extractions were performed in triplicate [20].

Antioxidant Capacity Analysis: The Ferric Reducing Antioxidant Power (FRAP), Reducing capacity measured by the Total Phenolic Content assay (TPC), and DPPH Radical Scavenging Activity assay were performed according to the protocol adopted by O'Sullivan et. al, 2025[5]. The results were expressed as mg of gallic acid equivalent per gram, mg GAE/g, for TPC, and as mg of ascorbic acid equivalent per gram, mg AAE/g, for FRAP and DPPH.

Nutritional calculation: The nutrient composition of the three formulations was calculated using ingredient data from the USDA FoodData Central (FDC) database, following the EuroFIR Guideline [21]. For each recipe, nutrient values were obtained for all ingredients from FDC, then summed by proportion and standardized to 100 g servings for comparison**.**

Statistical Analysis: All statistical evaluations were conducted using IBM SPSS Statistics software (version 28.0.1.1 (14). Data normality was assessed prior to selecting appropriate statistical tests. For parametric datasets, one-way ANOVA followed by the Least Significant Difference Fisher test (LSD) test for mean comparisons, and t-tests were used to compare means, while nonparametric data were analyzed using the Mann–Whitney U test and Kruskal-Wallis test. Data is shown as mean ±SEM. A p-value of < 0.05 was maintained throughout the analysis. Graphical representations were created using GraphPad Prism software version 8.0.c (GraphPad Software, Inc., San Diego, CA, USA).

RESULTS AND DISCUSSIONS

Texture Analysis: The texture analysis of the samples, measured as average Fmax (N), was evaluated on Day 1 and

Day 5 for SuC, StC, and InStC. For SuC, a significant increase in Fmax (N) was observed from Day 1 to Day 5($p < 0.05$) (**Supplementary Table S2)**. In contrast, the StC group did not show a significant difference in Fmax between Day 1 and Day 5 ($p > 0.05$). For InStC, Fmax was significantly higher on Day 1 compared to Day 5 ($p < 0.05$). Overall, these results demonstrate that storage time significantly affected the texture of SuC and InStC samples, but not StC, as indicated by the statistical analysis ($p > 0.05$).

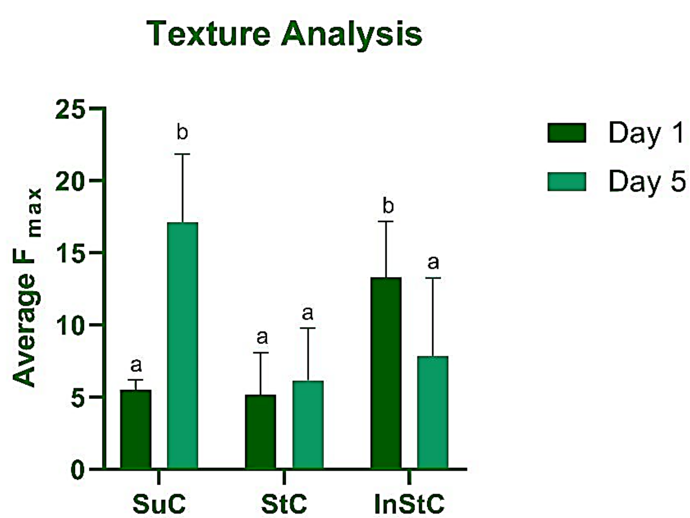

Figure 1. Bar graph showing the average maximum force (Fmax) measured during texture analysis of three cookie formulations: SuC, StC, and InStC. Measurements were taken on Day 1 and Day 5 of storage. Data are presented as mean ± standard deviation. Different lowercase letters above indicate statistically significant differences ($p < 0.05$).

On Day 1, the mean hardness values showed that InStC exhibited a significantly higher texture hardness (13.3 ± 3.8) compared to both StC (5.2 ± 2.9) and SuC (5.5 ± 0.7), suggesting that inulin contributed to increased structural integrity in the product. This result agrees with Tsatsaragkou et al. (2021) [22], who found that the presence of inulin can make hard dough biscuits denser and crunchier by absorbing water, thereby increasing hardness. By Day 5, a notable reduction in hardness was observed for InStC, while SuC showed an increase in hardness. SuC displaying the highest hardness (17.1 ± 4.7), followed by InStC (7.9 ± 5.4) and StC (6.2 ± 3.6) (Supplementary Table 2). The increased hardness in the SuC over time suggests crystallization or moisture migration, which is common in sugar-rich matrices. The decline in hardness for InStC aligns with hydration effects, likely due to inulin's water-binding capacity and differences in starch retrogradation. Overall, these findings suggest that inulin contributes to initial hardness, likely due to its network-forming properties, but does not sustain texture over time as effectively as sugar. Further optimization, such as combining inulin with hydrocolloids, may improve long-term textural stability.

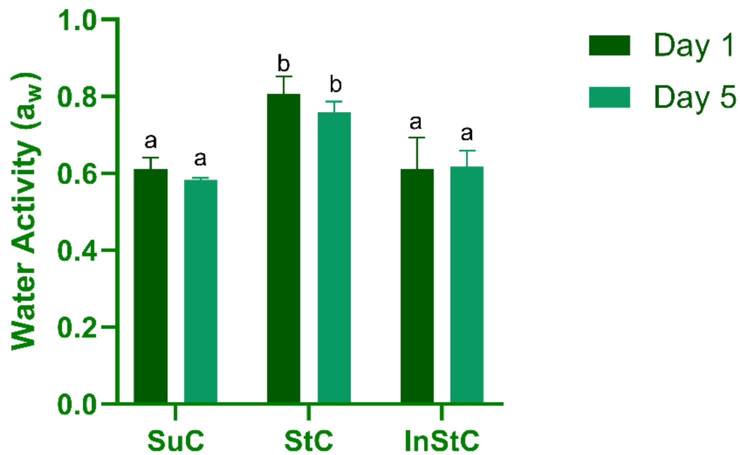

Figure 2. Water Activity of Cookie Formulations Over Storage Time (Day 1and Day 5). Data are presented as mean ± standard deviation. Different lowercase letters above indicate statistically significant differences ($p < 0.05$).

Water Activity: The water activity (a_w) of the samples was assessed on Day 1 and Day 5 for SuC, StC, and InStC. The results showed that the StC group exhibited significantly higher water activity compared to SuC and InStC on both days ($p < 0.05$) (**Supplementary Table S3)**. However, within each treatment, there were no significant differences in water activity between Day 1 and Day 5($p > 0.05$). Overall, the StC group maintained a higher water activity than the other treatments, and storage time did not significantly affect water activity across groups. A slight decrease is observed on day 5, but it remains higher than the other cookie types. Reb-A lacks the hygroscopic (water-binding) properties of sugar, leading to higher water activity. These suggest that Reb-A cookies may be less shelf-stable compared to sugar cookies [22-23]. For InStC, the water activity is similar to SuC and does not change much by day 5. Inulin has moisture-retention properties, helping maintain stability. A formulation containing just 5 g of inulin resulted in water activity (a_p) values similar to those observed in sugar-sweetened cookies containing 17.3 g of sugar, demonstrating that inulin can effectively mimic the moisture-retaining properties of sugar in cookie formulations, as observed for biscuits [22]. The stability of a_w suggests that adding inulin may help maintain texture and prevent excessive drying.

Antioxidant Assay: Comprehensive antioxidant analysis confirmed no significant differences between formulations across all assays ($p > 0.05$) (Figure 3), indicating that sweetener substitution did not substantially alter antioxidant capacity under the tested conditions (Supplementary Table S4).

Our findings contrast with those of Sulistyawati et al. (2024) [24], who reported significantly higher antioxidant activity in stevia cookies than in sucrose-based counterparts. This discrepancy likely stems from our use of purified Rebaudioside-A versus their whole-leaf stevia extracts. Whole stevia contains diverse phenolic compounds (e.g., chlorogenic acids, quercetin) that contribute to antioxidant capacity, whereas pure Rebaudioside-A lacks these ancillary phytochemicals.

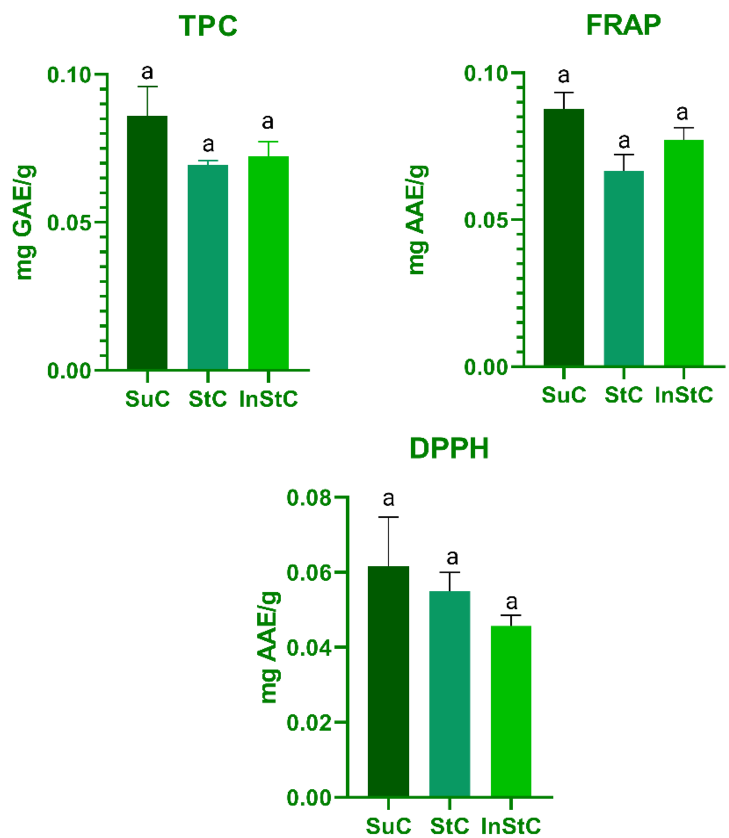

Figure 3: Antioxidant capacity assay results for SuC, StC, and InStC. (Created in BioRender. Hoffmann Sarda, F. (2025) https://BioRender.com/82ksttn) (Note: Statistical significance is determined by the letters a and b)

Nutritional Information of SuC, StC, and InStC: Table 1 presents the nutritional information for SuC, StC, and InStC. A comparative analysis of the three cookie samples revealed differences in dietary fiber, total energy, and sugar content. The dietary fiber content was highest in InStC (11.2 g/100 g), followed by StC (6.6 g/100 g), and lowest in SuC (5.7 g/100 g). In terms of total energy, SuC exhibited the highest caloric value (469 kcal/100 g), with StC and InStC providing 445 kcal/100 g and 433 kcal/100 g, respectively. Sugar content, inferred from available carbohydrate values, was also highest in SuC (59.4 g/100 g), decreasing in StC (44.5 g/100 g) and InStC (42.2 g/100 g). These results indicate that the InStC sample offers the highest dietary fiber content and the lowest energy and sugar content, suggesting a more favorable nutritional profile for individuals seeking higher fiber intake and reduced caloric and sugar intake.

Table 1: Nutritional information of SuC, StC, and InStC

	SuC	StC	InStC
Energy (kcal)	469	445	433
Fat (g)	20.8	24.0	22.8
Available Carbohydrates (g)	59.4	44.5	42.2
Fiber (g)	5.7	6.6	11.2
Protein (g)	8.2	9.5	9.0
Ash (g)	2.2	2.5	2.4

Table 2: Summary of the sensory analysis results for each parameter for the SuC, StC, and InStC.

Parameters	Measures	SuC	StC	InStC
Odor	Mean ± SD	5.9 ± 1.5	5.9 ± 1.5	6.2 ± 1.3
	Minimum	1.0	2.0	3.0
	Maximum	9.0	9.0	9.0
Color	Mean ± SD	6.7 ± 4.7	6.3 ± 1.5	6.7 ± 1.4
	Minimum	3.0	2.0	3.0
	Maximum	9.0	9.0	9.0
Taste	Mean ± SD	6.5 ± 1.5	5.5 ± 1.8	5.9 ± 1.7
	Minimum	2.0	2.0	1.0
	Maximum	9.0	9.0	9.0
Texture	Mean ± SD	6.4 ± 1.7	5.5 ± 1.8	6.3 ± 1.6
	Minimum	1.0	1.0	2.0
	Maximum	9.0	9.0	9.0
Aftertaste	Mean ± SD	6.3 ± 1.6	5.1 ± 1.8	5.2 ± 2.0
	Minimum	1.0	1.0	1.0
	Maximum	9.0	9.0	9.0
Sweetness	Mean ± SD	6.5 ± 1.6	5.3 ± 1.9	5.8 ± 1.8
	Minimum	0.0	1.0	0.0
	Maximum	9.0	9.0	9.0
Overall impression	Mean ± SD	6.6 ± 1.4	5.4 ± 1.7	5.9 ± 1.5
	Minimum	2.0	1.0	3.0
	Maximum	9.0	9.0	9.0

Sensory Analysis: Post-hoc pairwise comparisons revealed that, for odor and color, no statistically significant differences were observed between any groups ($p > 0.05$). For taste, the SuC scored highest (6.5 ± 1.5), followed by InStC (5.9 ± 1.7), with StC receiving the lowest rating (5.5 ± 1.8). A significant difference was found between StC and SuC (adjusted $p < 0.001$), while StC vs InStC ($p = 0.224$) and InStC vs SuC ($p = 0.062$) were not significant in terms of taste. After-taste showed significant differences between StC and SuC ($p < 0.001$) and between InStC and SuC ($p < 0.001$), but not between StC and InStC ($p = 1.000$). In texture, StC differed significantly from both InStC ($p = 0.004$) and SuC ($p < 0.001$), while InStC and SuC did not differ ($p = 1.000$). For sweeteners, SuC received the highest score (6.5 ± 1.6), followed by InStC (5.8 ± 1.8) and then StC (5.3 ± 1.9). Significant differences were found between StC and SuC ($p < 0.001$) and InStC and SuC ($p = 0.003$), but not between StC and InStC ($p = 0.281$). Similarly, for the overall impression, InStC received a higher mean score

(5.9 ± 1.5) than StC (5.4 ± 1.7), although both were lower than SuC (6.6 ± 1.4). StC and SuC ($p < 0.001$) and InStC and SuC ($p = 0.001$) differed significantly, with no significant difference between StC and InStC ($p = 0.123$). In conclusion, although the SuC was rated highest across all parameters, the InStC consistently outperformed the StC in terms of taste, texture, sweetness, and overall impression. The results suggest that the addition of Inulin has improved the taste of Reb-A sweetened cookies.

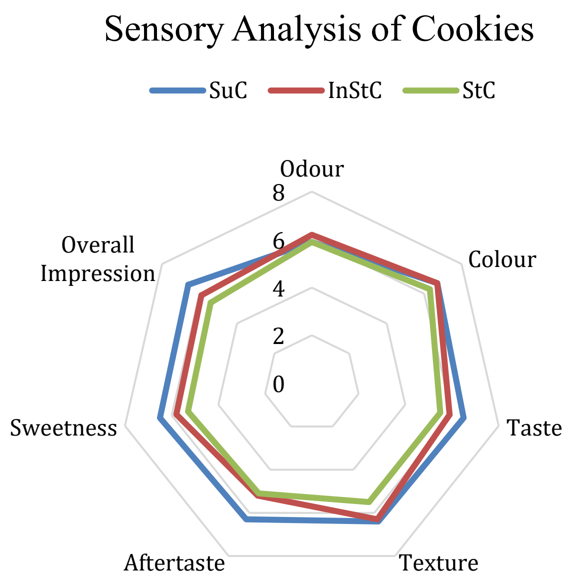

Figure 4: Spider diagram for the SuC, StC, and the InStC. This diagram displays the mean results for the following parameters: odor, color, taste, texture, aftertaste, sweeteners, and overall impression.

The spider diagram (Figure 4) shows that SuC received the highest sensory scores across all attributes. InStC performed closely to SuC, especially in odor, color, and texture, while StC had the lowest scores, particularly in aftertaste and overall impression. This suggests that inulin combined with Reb-A is a more acceptable alternative than only Reb-A.

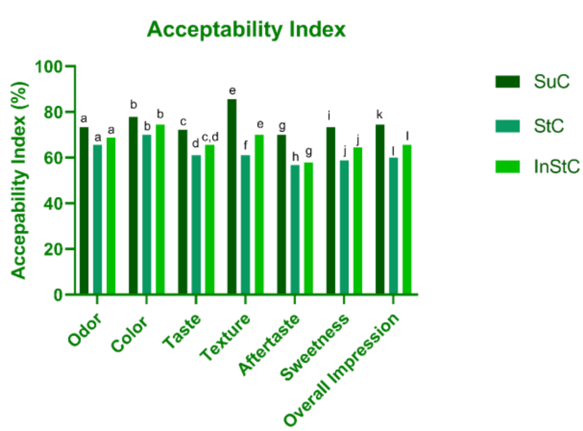

Figure 5: The AI (%) for odor, color, taste, texture, aftertaste, sweetness, and the overall impression of the SuC, StC, and InStC amongst participants of the sensory analysis

Acceptability Index: All samples had AI values above 60%, with sugar SuC showing the highest acceptability. InStC outperformed StC in taste, texture, and overall impression. SuC had the highest AI, followed by InStC, both above 70%, indicating good acceptance. StC scored lowest in aftertaste, sweetness, and overall impression but remained moderately acceptable. Pairwise comparisons showed no significant differences in odor and color among groups. Significant taste differences were found between StC and SuC (adjusted $p < 0.001$), but not between StC and InStC (adjusted $p = 0.226$) or InStC and SuC (adjusted $p = 0.078$). For texture, significant differences were observed between StC and InStC ($p = 0.004$) and StC and SuC ($p < 0.001$), but not between InStC and SuC ($p = 1.000$). Aftertaste showed the same pattern: StC vs. InStC ($p = 0.004$), StC vs. SuC ($p < 0.001$), InStC vs. SuC ($p = 1.000$). For sweetness, SuC differed from StC ($p < 0.001$) and InStC ($p = 0.003$), but StC and InStC did not differ ($p = 0.281$). Overall impression was significantly different between StC and SuC ($p < 0.001$), InStC and SuC ($p = 0.001$), but not between StC and InStC ($p = 0.123$).

CONCLUSION

This study demonstrates that replacing sugar with Rebaudioside-A and incorporating Inulin in gluten-free cookies is a novel and viable approach for developing functional, low-calorie snacks. While Reb-A alone posed challenges in aftertaste acceptability, adding inulin improved the sensory profile, in terms of taste and texture. Future research should explore ways to sustain texture modifications to enhance consumer preference for Reb-A-based baked goods. The outcomes of this study validate the formulation of Reb-A-based oats and quinoa cookies, incorporating inulin, which improves texture and overall sensory acceptance by increasing fiber content and reducing calories.

List of Abbreviations: Reb-A: Rebaudioside A; SuC: Sugar-based Cookies; StC: Rebaudioside-A based; InStC: Rebaudioside-A+ inulin based.

Authors' Contributions: FHS conceptualized the research and led the project. AB, MIW, GR, and MP developed the product and conducted analyses. DG standardized the antioxidant capacity assays. AB and MIW drafted the manuscript. AB, MIW, and GR performed statistical analyses. FHS and DG provided guidance, critical review, and contributed to discussions and manuscript preparation. All authors approved the final article.

Competing Interests: The authors declare that they have no competing interests.

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