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Key quality dimensions for gluten-free bread perceived by general and non-gluten consumers: A case study with apple pomace and flaxseed

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ABSTRACT

This study aimed to evaluate the sensory perception of a gluten-free bread formulated with sustainable and locally sourced ingredients: apple pomace and flaxseed. Sensory evaluation was performed with gluten-free and gluten consumers to analyze the differences in perception based on consumption patterns and to identify the key quality attributes influencing acceptability. Results showed that the formulations containing up to 6 % apple pomace and 12 % flaxseed resulted in the most acceptable products for both consumers group. However, higher levels of apple pomace (10 %) led to lower scores, and no significant differences in overall acceptability were found between both consumers groups. Nevertheless, gluten-free consumers tended to provide more detailed sensory descriptions, particularly for texture attributes, likely due to their need to evaluate newly formulated products with a great variability in their characteristics. “Crispy”, “Light texture” and “artisan-like appearance”, among others, were identified as positive attributes, while “rubbery” emerged as the main negative factor affecting acceptability. Based on these findings, a decision tree was proposed as a tool to evaluate gluten-free bread, balancing defects and positive sensory characteristics. This approach could guide manufacturers in developing gluten-free breads that meet the expectations of people with different consumption patterns.

1. Introduction

Bread is a staple food worldwide (Capurso, 2024; Cione et al., 2021), and in Mediterranean countries it represents the principal source of carbohydrates, along with other products such as pasta, rice and potatoes (Serra-Majem et al., 2019). Globally, celiac disease affects 1.4 % of the population according to serologic studies, highlighting its clinical relevance and the need for gluten-free (GF) alternatives in food development (Singh et al., 2018). Moreover, almost 5 % of the population cannot consume it because of health-related reasons (such as celiac disease and non-celiac gluten intolerance) and around 10 % removes it from the diet for other reasons (Bascuñán et al., 2018; Kim et al., 2017). In spite of the ascending demand for GF products, GF bread (GFB), still has relevant disadvantages when compared to bread made with gluten-containing grains: it is at least two times more expensive (Zerbini et al., 2024), it is usually sold frozen, and once prepared for consumption, the shelf life is a significant concern due to its tendency to stale quickly and its susceptibility on microbial contamination (Capriles et al., 2023; Łopusiewicz et al., 2023).

Consumption of GF products in the non-celiac population seems to be associated with the belief that GF products are healthier, although related studies are controversial. Mármol-Soler et al. (2022) mentioned that despite de improvements in GF products, they are not equivalents to their gluten containing homologues yet. In the same way, other authors

Abbreviations: GF, gluten-free; GFB, gluten-free bread; G-consumers, gluten consumers, refers to general population with no dietary restrictions.; GF-consumers, non-gluten consumers; APP, apple pomace powder.

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reported that GF versions are nutritionally deficient, with lower levels of proteins, and micronutrients. On the contrary, a significate amount of GFB has fiber content higher than gluten containing breads (Cornicelli et al., 2018; Fajardo et al., 2020), thus they might contribute to greater intake. However, studies show great variability regarding fiber content (Allen and Orfila, 2018). Taste and texture quality have improved in recent years (Tóth et al., 2022), thus these advances in innovative GFB-making involve the employment of hydrocolloid additives (Culetu et al., 2021; Moradi et al., 2021; Torres-Pérez et al., 2024). Additionally, there are other broadly used ingredients such as psyllium, which has shown to improve texture and shelf life characteristics of GFB (Filipčev et al., 2021; Fratelli et al., 2021). However, the use of psyllium arises some concern on sustainability, as it is mainly imported from India and Pakistan (Katke et al., 2020).

Addressing sustainability is crucial in GF food production to contribute to the search of solutions for the climate crisis, whose consequences demand urgent actions (Ammann et al., 2023). In this context, the use of locally produced ingredients should be prioritized, such as flaxseed, which, with a mucilage fraction which is known to enhance texture, as well as its nutritional properties (Ahmadinia et al., 2023) could replace psyllium and hydrocolloids. Most existing studies on flaxseed in GFB have mainly focused on flaxseed oil cake (a by-product from oil-extraction) or on processed forms like soluble extracts and flaxseed flour (Krupa-Kozak et al., 2022; Łopusiewicz et al., 2023). Additionally, upcycling ingredients from agro-food industries, such as apple pomace, could, on the one hand, enhance nutritional characteristics and provide natural fibers, antioxidants and other micronutrients and, on the other hand, it would reduce the environmental impact of bread as it replaces a portion of flours (Cantero-Ruiz de Eguino, 2024).

Sensory and consumer research plays a crucial role in the design and development of new food products (Ruiz-Capillas et al., 2021). Although bread is the most investigated GF products, with about 7000 published articles in the last decade, only 32 % included some sensory analysis. As reviewed by Capriles et al. (2023), there are still few studies that include consumers diagnosed with celiac disease or those adhering to a GF diet. Conducting such studies would enable to examine different consumer segments and their specific consumption habits, promoting the development of consumer-tailored GF products. Moreover, individual sensory background may strongly influence food preferences (Costell et al., 2010), making it more important to conduct studies that analyze these individual differences. Capriles et al. (2023) also emphasize that in most sensory studies about GFB the evaluation of overall linking is performed by non-celiac consumers, which may not accurately reflect the preferences of the target population. In those cases that celiac or non-gluten consumers participated, it was often as experts or as part of a trained panel, although acceptability should be assessed by non-trained consumers (Lawless and Heymann, 2010; Taghdir et al., 2017; Ziobro et al., 2013) Additionally, as highlighted by Capriles et al. (2023), it is important to consider the low number of participants in hedonic tests, which remains as a recurrent limitation in sensory studies on GFB. Insights on the acceptability criteria of gluten-consumers and non-gluten consumers could help tailoring new products in two possible ways: adapting them to specific requirements or using commonly required criteria to design staple food for anyone.

The aims of this study were to find the best formulation of GFB based on apple pomace and flaxseed, comparing usual GF consumers and general population, and to identify possible key sensory features which may condition the sensory evaluation in each of those consumer segments.

2. Materials and methods

2.1. Ingredients and bread making

A base formulation with flour and starches was used for GF dough preparation, and apple pomace and locally produced flaxseed were incorporated for the first time together in GFB making. Apple pomace was collected from a local ciderhouse (Zapiain Scoop., Gipuzkoa). Apple pomace powder (APP) was obtained after washing, dehydrating and grounding the waste as previously reported (Cantero et al., 2022). Flaxseed (***Linum usitatissimum)*** was locally cultivated and whole seeds were treated by an aqueous process with distilled water to extract the mucilage (Ziolkovska, 2012). The use of whole seeds allowed the full valorization of the ingredient, incorporating both the mucilage and the nutritional components of the seed itself. This approach reduces processing and helps avoiding sensory issues, such as bitterness reported in flaxseed flour, which could negatively affect consumer acceptability (Zhang et al., 2023).

The base formulation was made using a variety of ingredients, including cornstarch (23–27 % [depending on the formulation]), a mix of rice, corn and buckwheat flours (66–74 %), salt, oil, sugar, yeast and water. Experimental breads were obtained replacing the mix of flours and starches with APP at different quantities. Flaxseed was added in different amounts and water content was adjusted based on previous experiences (Cantero et al., 2022). . All the doughs were mixed in a kneading machine, fermented for 1,5 h at 24 °C and baked for 1 h at 210 °C. Samples were cooled at room temperature for 3 h before the consumer test.

The process was carried out sequentially, first adjusting the formulations (ingredient and water proportions, as well as process variables) and second, through advice by a panel of members who were familiarized with the product. In these initial stages, three formulations were selected as samples for the consumer test: A0F12 (0 % APP, 12 % flaxseed), A6F12 (6 % APP, 12 % flaxseed) and A10F6 (10 % APP, 6 % flaxseed).

2.2. Consumers

A group of 157 consumers was recruited through the sensory testing database of the Laboratory of Sensory Analysis of the UPV/EHU (LASEHU), students and employees of the University of the Basque Country, Celiac Association of Basque Country (EZE), Association of Celiac and Family of Celiac Álava (EZEBA) and diffusion through networks and radio. Possible participants filled out an online questionnaire about personal and demographic information and availability. Consumers were selected to try to obtain an equal group in terms of GFB consumption habit. Regarding this feature, people diagnosed with any symptoms regarding gluten, people used to consume GF products for any other reason and people who never consumed GF products were identified. The first two were tagged as “non gluten-consumers”, while the last ones were the “gluten-consumers”, GF-consumers and G-consumers, respectively.

2.3. Sensory trials

The sensory analysis was performed in individual cabins at the Laboratory of Sensory Analysis of the University of the Basque Country (LASEHU). Participants attended a single session, which lasted approximately one hour. For the test, samples were cut into 2 cm thick slices (including crumb and crust), coded with a three-digit number and served in a tray. Samples were presented in a randomized order using a Williams Latin square design, generated by FIZZ software version 2.40H (Biosystemes, Couternon, France), as in the methodology described in previous studies (Ojeda et al., 2021) . The session was divided into three parts. In the first part, participants evaluated the samples in three stages; for each sample, they first rated the overall acceptability of the appearance in a 10 cm continuous scale (0 = “I dont́ like it at all” and 10 = “I like it a lot”). Pictures of the entire bread were evaluated for assessment of the external appearance and a slice of bread for the internal appearance. After this, participants tasted each sample and rated the flavor and texture acceptability. Then, they were asked about their

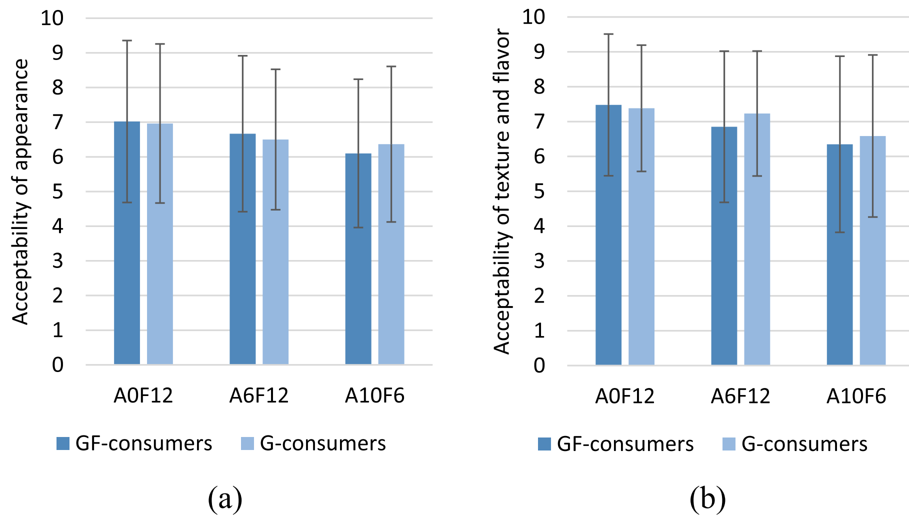

Fig. 1. Acceptability of appearance (Fig. 1a) and texture and flavor (Fig. 1b) of gluten-free breads analyzed in the consumer test for each consumer group, those accustomed to gluten-free products (GF-consumers) and those who are not (G-consumers). A0F12, 0 % apple pomace powder and 12 % flaxseed; A6F12, 6 % of apple pomace powder and 12 % flaxseed; A10F6, 10 % of apple pomace powder and 6 % flaxseed.

willingness to purchase the bread, how often they would buy it, and the price they would be willing to pay. This process was repeated sequentially for each sample. In the second part, participants were given a new set of the same three breads, but with different codes. In this part, they made the evaluation in two stages: first, they performed Check All That Apply (CATA) test for appearance (using 13 descriptors) and then for texture and flavor (28 descriptors). They repeated the evaluation sequentially for each sample. Finally, participants completed a short questionnaire concerning their GF or conventional bread consumption habits and preferences. The design of the sessions and the collection of data was made by FIZZ 2.40H software.

2.4. Statistical analysis

Descriptive statistic was performed to analyze the responses of the questionnaire and the acceptability of the samples. Possible significant differences ($p < 0.05$) between breads were analyze by means of Kruskal Wallis test and differences between G- and GF-consumers by Mann-Whitney test. These analyses were conducted using IBM SPSS Statistics v28 (Armonk, NY, USA). Agglomerative hierarchical clustering was performed utilizing Euclidean distance and Ward's method for aggregation and CATA data analysis by Cochran's Q. Moreover, CLUSCATA was used to quantify homogeneity index of each group (G- and GF-consumers) and adjusted RV coefficient ($p < 0.05$) to determine possible similarity between both consumer profiles (El Ghaziri and Qannari, 2015) . Additionally, regression trees were constructed to explore the relationship between sensory attributes and acceptability scores through CART (Classification and Regression Trees) methodology. These analyses were performed using XLSTAT Sensory v2024.3 (Addinsoft, Paris, France).

2.5. Ethical considerations

This study was conducted in accordance with ethical standards and approved by the ethics committee of the University of the Basque Country (approval number: M10_2023_054). All participants provided informed consent prior to participation, and the study adhered to guidelines ensuring the privacy and confidentiality of participants, particularly regarding health related information such as celiac status.

3. Results and discussion

3.1. Consumers' profile

From the 157 participants in the consumer test, the 69.5 % were female and 30.5 % male. The age distribution was balanced, with 35.03 % between 18 and 35 years old, 31.85 % between 36 and 50, and 33.12 % between 51 and 65. Regarding consumption habits, 45.86 % were used to consume GFB and 54.14 % never consumed it. Among those who were used to consume GFB, 65.28 % were diagnosed with celiac disease and 34.72 % were not. With the agglomerative hierarchical clustering analysis, consumers were grouped into two clusters according to the acceptability of the products (summarized in S1). Profiles of the participants grouped in one or the other cluster did not differ significantly.

3.2. Questionnaire about consumption habits and preferences

According to the data gathered in the questionnaire, gender did not affect responses. However, there was a higher proportion of female participants compared to male participants, so this factor limited the analysis of differences between genders. Among ages, differences ($p \leq 0.05$) were observed only in one question: 'What factors are important to you when choosing which bread to buy?' The participants between 51 and 65 years old prioritize healthiness more than consumers aged 18–35. However, more differences ($p \leq 0.05$) were noted in responses between the group accustomed to GF products and those who dont́ consume them. The question about aspects that could be improved in commercial GFB revealed that GF-consumers highlighted the importance of improving taste, texture and shelf life which agrees with conclusions from other authors (Calix-Rivera et al., 2023; Tóth et al., 2022). Frequency of GFB consumption was also analyzed among GF-consumers: 41.7 % consume it daily, 12.5 % consume it 2–3 times per week, 16.6 % declared to consume it 1–3 times per month, while 29.2 % never or hardly ever do. Despite bread being one of the most common foods in the Mediterranean diet, <50 % consumed it daily when it is GF, which suggests that either the availability or the quality of GFB may not be the same of the conventional bread ones, as other authors mentioned in previous works (Roman et al., 2019; Tóth et al., 2022). However, Alencar et al. (2021) indicated that 93 % of the celiac consumers in their study were used to consume different GFB daily. Despite this frequency of consumption, they also highlighted several issues in this product, such as taste, price and texture, underscoring the need for further

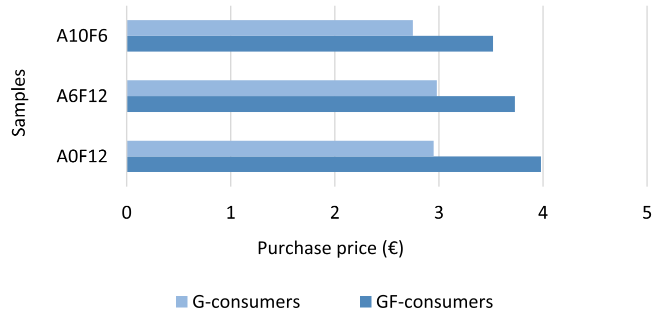

Fig. 2. The price that consumers accustomed to gluten-free products (GF-consumers) and those who are not (G-consumers) would be willing to pay for each sample. A0F12, 0 % apple pomace powder and 12 % flaxseed; A6F12, 6 % of apple pomace powder and 12 % flaxseed; A10F6, 10 % of apple pomace powder and 6 % flaxseed.

improvements

Considering all the consumers who participated in the test, the results of the rest of items of the questionnaire revealed a diverse range of preferences in bread types and formats. When they were asked about their preferred bread format, 31 % chose round bread, followed by 28 % who preferred baguettes, 23 % ciabatta, 12 % sandwich bread, and 6 % selected other formats. Regarding the type of bread, 37 % of participants preferred white bread, while 27 % chose whole grain bread, 20 % artisan bread and 16 % indicated other types of bread. Finally, when considering important factors when purchasing bread, 41 % of consumers prioritized health, 20 % considered price, 18 % being artisan and 21 % indicated aspects such flavor and texture. These findings highlighted the varied preferences and considerations that influence consumer choices in the bread market.

3.3. Acceptability and purchase intentions

The majority of consumers indicated they would purchase the three samples analyzed: 93 % would buy A0F12, 87.9 % would buy A6F12, and 83.4 % would buy A10F6. Among those willing to purchase the products, 49 % would buy A0F12 at least three times per week, 45.9 % would buy A6F12 and 5.6 % would buy A10F6 with the same frequency.

Fig. 1 shows the perceived acceptability by the two consumers groups for appearance, as well as texture and flavor attributes. In both groups the sample containing 10 % of APP received significantly lower scores ($p < 0.05$) than the others for both appearance and texture-flavor. In contrast, no significant differences were observed between the highest-rated samples: A0F12 and A6F12.

Consumers who indicated they would purchase the products were also asked how much they would pay for a loaf. There were no significant differences among the prices indicated for each bread. However, there were significant differences between G- and GF-consumers, as GF-consumers assigned higher prices to all the samples, as shown in Fig. 2.

GF foods generally have higher prices compared to their gluten-containing counterparts, and several authors have noted that people following a GF diet frequently demand fairer prices (Myhrstad et al., 2021; Vriesekoop et al., 2020). In this case, we observed that the purchasing experience of each consumer influenced the price that they were willing to pay for the products. Similarly, after a study analyzing the prices of GF products in various supermarkets across Spain, De Las Heras-Delgado et al. (2021) after a study analyzing the prices of GF products in various supermarkets across Spain concluded that consumers are used to pay up to four times for GF products compared to their gluten-containing counterparts.

Table 1
Absolute frequencies of significant sensory descriptors checked for the different formulations of gluten-free bread among all consumers: A0F12 (0 % apple pomace powder and 12 % flaxseed), A6F12 (6 % apple pomace powder and 12 % flaxseed), and A10F6 (10 % apple pomace powder and 6 % flaxseed).

	Descriptors	Samples			p-values (Cochran's Q)
		A0F12	A6F12	A10F6	
Appearance	Toasted crust	24^c	95^b	121^a	<0,0001
	Lightly toasted crust	50^a	7^b	6^b	<0,0001
	Excessively dark crust	1^c	27^b	47^a	<0,0001
	Whole grain-like	44^b	110^a	108^a	<0,0001
	Appetizing	121^a	96^b	74^c	<0,0001
	Excessively dark crumb	1^c	29^b	72^a	<0,0001
Texture-flavor-aromas	Intense smell	48^b	76^a	79^a	<0,0001
	Weak smell	74^a	48^b	45^b	0000
	Cereal notes	107^a	101^a	75^b	0000
	Dense texture	80^b	99^a	91^{ab}	0028
	Light texture	33^a	16^b	12^b	0000
	Toasted notes	31^b	64^a	68^a	<0,0001
	Fruit notes	12^b	17^{ab}	25^a	0046
	Crumbly	38^{ab}	50^a	34^b	0041
	Acid	4^b	16^a	25^a	<0,0001
	Bitter	14^b	37^a	43^a	<0,0001
	Whole grain-like	51^b	104^a	101^a	<0,0001
	Crispy	70^a	54^{ab}	51^b	0011

Letters (a, b, c) stand for significant differences ($p < 0.05$) between samples for each descriptor.

3.4. Descriptive analysis

3.4.1. Frequency of the attributes in check all that apply

Results of CATA highlighted the impact of APP addition, consistent with previous studies. APP contributed to a darker color usually associated with whole grain-like appearance and to denser texture, linked to its fiber content (Lu et al., 2021; Messina et al., 2024; Ren et al., 2020). Furthermore, A6F12 and A10F6 were perceived more as "toasted crust", due to the Maillard reaction that occurred by APP in the baking process (Çelik and Gökmen, 2020) . Of the 41 descriptors evaluated in the test, 18 showed significant differences in how often they were marked across samples, as detailed in Table 1.

When comparing GF- and G- consumers, notable differences were observed in their perceptions of the samples. GF-consumers selected the attribute "consistent appearance" more frequently for A6F12 than for the other samples, even though this descriptor wasńt significant in the overall analysis (Table 1), unlike a similar attribute: "dense texture". The sample with 10 % of APP was marked as the hardest and driest by GF-consumers, while G-consumers marked the samples similarly for those attributes. GF-consumers also paid less attention to attributes like "cereal aroma" and "fruit aroma", which contrasted with the overall findings. On the other hand, G-consumers, did not found descriptors like "crispy texture" and "light texture" to differ between samples. A higher number of consumers marked sample A10F6 as having "fruity notes" while it was the least selected for the attribute "salty". These differences might suggest that familiarity with GF products led to a greater focus on textural characteristics, while less experienced consumers tended to prioritize flavor profiles.

3.4.2. Influence of consumer profile in the identification of key sensory attributes

In this section, the attributes with a positive and negative effect on the mean acceptability score are presented. Although no differences were found in overall acceptability between G-consumers and GF-consumers, distinct attributes influencing their perceptions were identified, as shown in Fig. 3.

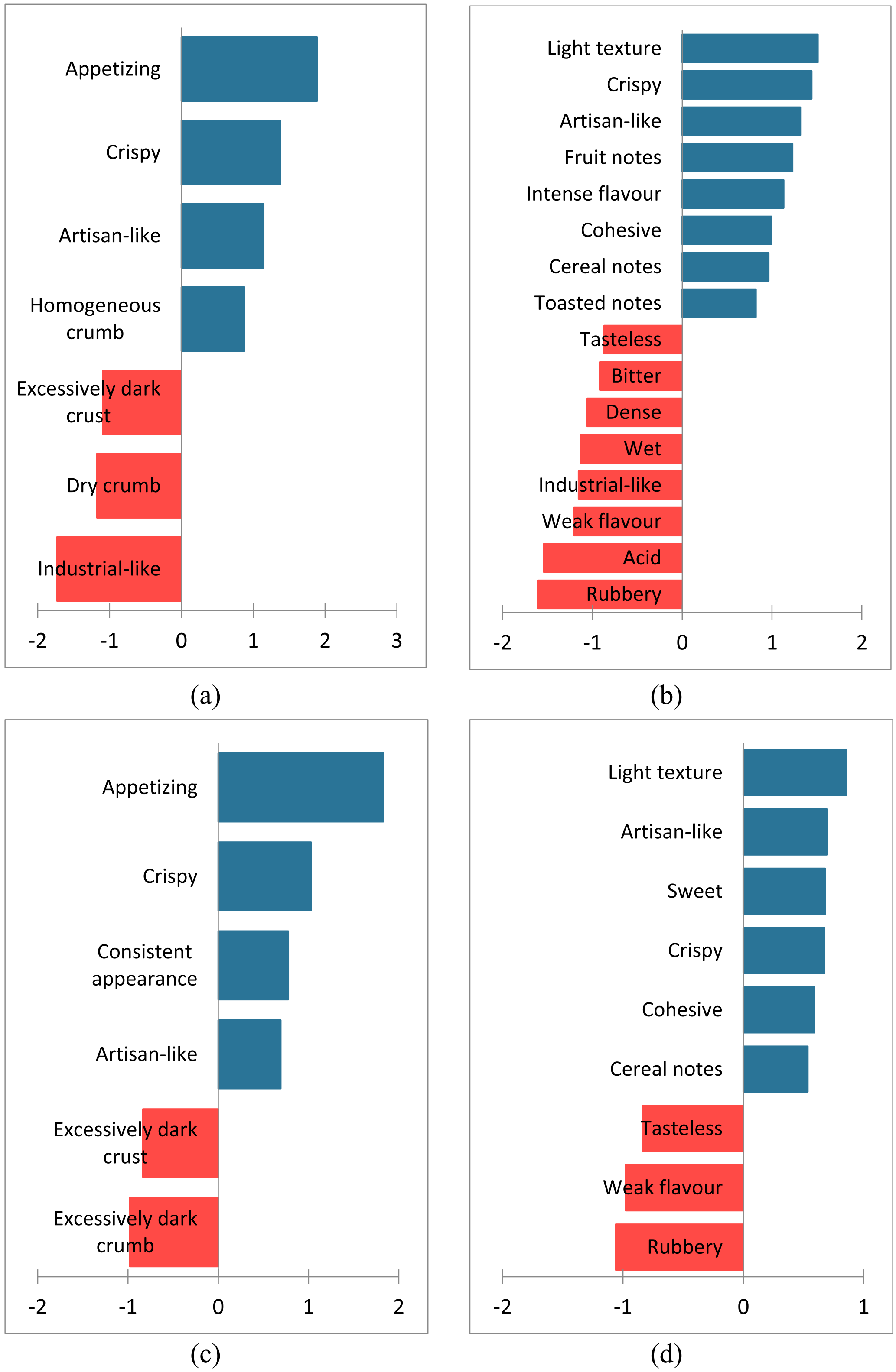

Fig. 3. Load of each characteristic on acceptability scores, regarding the appearance (Fig. 3a) and texture, flavor and aromatic characteristics (Fig. 3b) of the **GF-consumers group,** and Fig. 3c regarding appearance and Fig. 3d texture, flavor and aromatic characteristics of the **G-consumers group**.

Breshears and Crowe (2013) conducted a sensory test with both GF- and G-consumers as well, not specified if they suffered celiac disease, to analyze potential differences in product liking between consumers groups. Similar to our results, they concluded that there werent significant differences, but it should be noted that they did not perform any descriptive analysis.

In our study and for GF-consumers, acceptance was influenced by a broader range of descriptors compared to those who are not familiar with such products. GF-consumers appeared to analyze texture more exhaustively, identifying more textural attributes that may impact

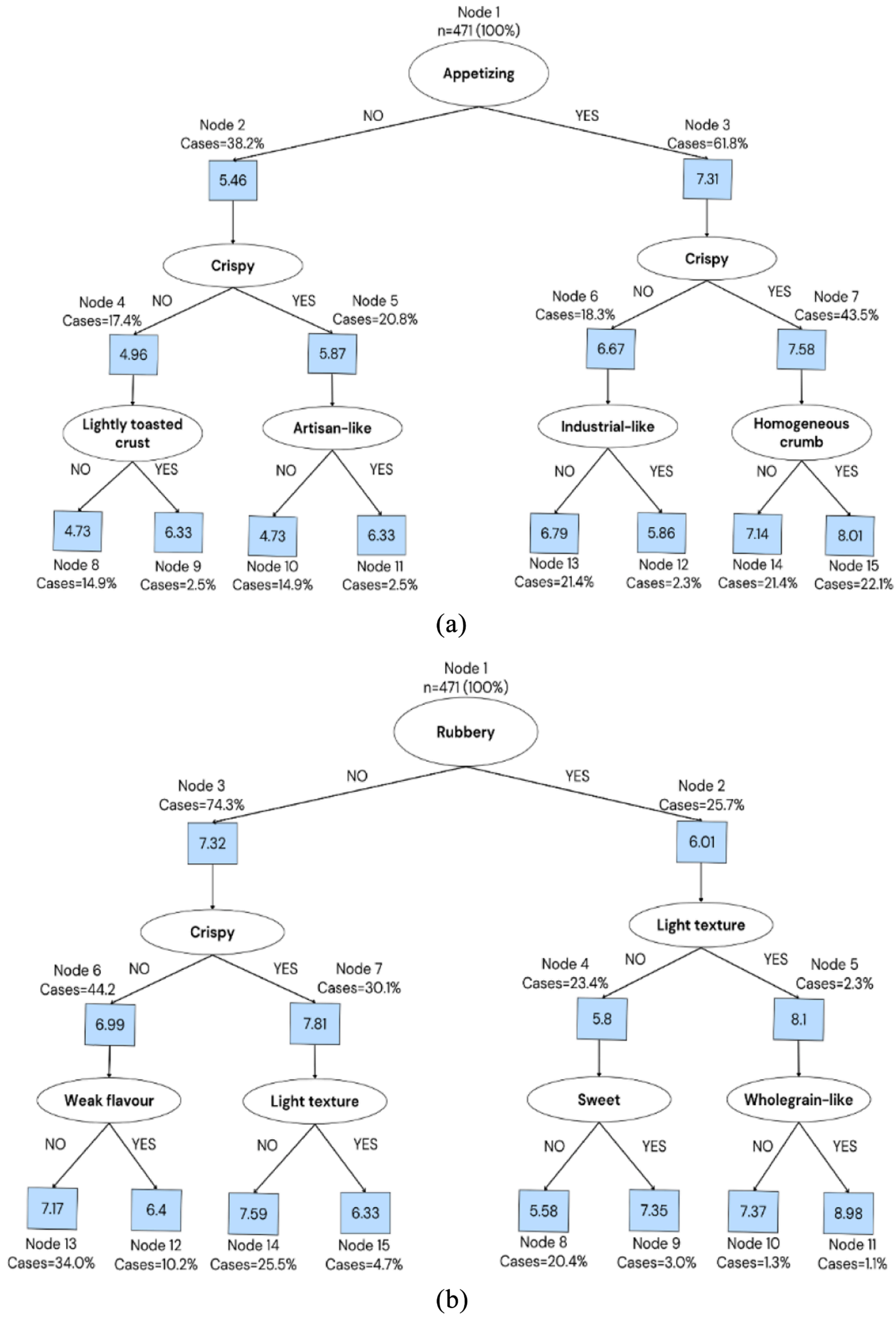

Fig. 4. Regression trees based on Check All That Apply data and acceptability scores (in score boxes), regarding appearance (4a) and flavor and texture characteristics (4b).

acceptance. In contrast, G-consumers noted with higher frequency "homogeneous crumb", "cohesive" and "dry crumb". This might suggest that GF-consumers were more sensitive to or more conscious of texture details, and it is probably related to the fact that texture characteristics of the current commercial GFBs are usually evaluated as not ideal. Similar descriptor arose in other studies using CATA test for GFBs. For example, Laignier et al. (2022) descriptors such as "dry", "grainy" and "compact"; similarly, Santos et al. (2021) noted "crumbly" and "uniform alveoli" as critical descriptors. A greater brunch of descriptors related to flavor and aromas impacted significantly in the acceptability score of GF-consumers, compared to the group of G-consumers, some of the most mentioned ones being "cereal notes", "toasted notes", "bitter" and "fruit notes". GF-consumers, familiar with the limitations of commercial GFBs in taste and texture (Toth et al., 2020), might tend to do a more exhaustive sensory evaluation.

The homogeneity index was used to analyze the similarity of CATA responses among the assessors within the same group. For GF-consumers the homogeneity index was 0.554 and for G-consumers 0.585, indicating similar level of agreement for both groups, although slightly higher within the second group. Although the homogeneity indexes observed in this study are moderate, lower indices have been reported (An and Lee, 2024; Llobell et al., 2019). Several studies suggested that consumption frequency influences sensory perception and response patterns, frequent consumers tend to detect product characteristics more easily, leading to different sensory profiles compared to infrequent consumers, affecting response consistency (An and Lee, 2024). Jeong & Lee (2021) indicated that familiarity enhances discrimination ability and agreement among responses. Given the unclear standards for food regarding homogeneity indexes, further research is needed to clarify the relationship between consumption frequency and homogeneity in sensory characterization. We could understand that GF consumers are more familiar to GF products and that we would expect a higher homogeneity index. However, commercial GF breads vary greatly in characteristics, which makes it more difficult for consumers to evaluate comparing to a certain standard, while gluten-containing breads are generally more standardized and less likely to exhibit atypical descriptors such as "rubbery" and "tasteless", common in GF breads.

Complementing these results, the RV coefficient was also analyzed to compare CATA results from both consumer groups. For appearance data, results showed a RV coefficient of 0.958 ($p < 0.01$) between both datasets suggesting a high degree of similarity. Regarding texture and flavor, the RV coefficient was 0.884 ($p < 0.01$). Indeed, in spite of the differences in the amount of attributes marked in G-consumers and GF-consumers, there were key descriptors mentioned in both groups, such as "crispy", "artisan-like", "light texture", "cereal notes" or "cohesive" for positive loads, and "dark crust", "tasteless", "weak flavor" or "rubbery" for negative loads (Fig. 3). However, they were not always ranked identically and, as explained before, evaluation by GF-consumer was richer, especially referring to flavor and texture.

For those samples receiving the highest scores for acceptability (A0F12 and A6F12), attributes such as "wholegrain-like", "appetizing", "intense smell", "fruity notes", "light texture", and "crispy" were marked more frequently in the CATA test (Table 1), which were characteristics loading positively with higher acceptability ratings.

Although the CATA results showed a positive link between "artisan-like" appearance and acceptability, the initial questionnaire revealed a preference for white bread. This could be due to the sensory experience during the tasting, where artisan-like appearance enhances positive perception, while factors like habits, convenience or price influence preferences in general. Additionally, confusion between the questions on 'preferred' vs. 'usually consumed' bread may have contributed to this discrepancy. Moreover, GF products offer fewer artisan options, which could also affect consumer choices.

3.4.3. Regression tree analysis for the acceptability of gluten-free bread

To further understand the characteristics that influenced the acceptability of the samples, a regression tree analysis was conducted using sensory variables. This approach, along with the data of Fig. 3, enables the identification of key attributes that influence consumer preference (Carrillo et al., 2023).

Fig. 4 shows routes or combinations of descriptors which lead to higher or lower degree of acceptance. Results for appearance are presented in (a) and results for flavor and texture are presented in (b). Crispy, light texture, intense flavor and artisan-like are extracted as main positive attributes in the acceptance routes, similarly to Fig. 3. Appetizing, being a subjective aspect, it was consolidated as the main factor affecting preferences related to appearance. In the study of Ángel-Rendón et al. (2020) it was concluded that the acceptability (of pork meat, in that case) was higher when the samples were perceived as "appetizing", coinciding with other authors (Andersen et al., 2022; Głuchowski et al., 2024)(. For flavor and texture, rubbery appeared as the main factor (in this case, with a negative effect) followed by crispy. Acceptability scores above 6 could be reached by GFB not being "rubbery" and being "crispy" and having a light texture or when they have a light texture but are wholegrain-like, in spite of having rubbery texture. Similarly, other studies have also reported that the "rubbery" attribute was negatively correlated with the preference for GFB (do Nascimento et al., 2017; Laureati et al., 2012)(do Nascimento et al., 2017; Laureati et al., 2012) . This tool could be useful for the design and development of GFB, helping to optimize sensory attributes that drive consumer acceptance, either to confirm its external validity, or to complete or adapt it.

Table 2
Definition of key positive attributes negative characteristics of gluten-free bread.

	Term	Definition
Positive descriptors	Light texture	Refers to a bread with a soft and airy crumb structure that feels light when held or eaten (Heuven et al., 2024).
	Crispy	A dry rigid crust which, when bitten with the incisors, fractures quickly, easily and totally while emitting a relatively loud, high-pitched sound (Tunick et al., 2013).
	Artisan-like	Refers to the appearance and texture of bread that evokes traditional bread making. It implies bread with an irregular shape, a golden crust and a uniform crumb, as well as deeper and more complex flavor (*ad hoc* definition).
	Cohesive	Refers to crumb texture. It indicates that bread has a compact structure and maintains its shape without crumbling or breaking when chewing (Banach et al., 2016).
	Homogeneous crumb	Indicates a crumb with a uniform distribution and size of alveolus (*ad hoc* definition).
	Cereal notes	Contains aromas of typical cereals used in bread making.
	Fruit notes	Contains fruity aromas.
Negative characteristics	Rubbery	Duration required to break and swallow a piece of bread, reflecting the persistent density during chewing (Morais et al., 2014).
	Weak flavor	Refers to a bread lacking in taste intensity or complexity (*ad hoc* definition).
	Excessively dark crust	Indicates a crust darker than desired, which has been baked for too long or at an excessively high temperature (*ad hoc* definition).
	Wet	Describes bread with excessive moisture content, resulting in a soggy texture, often due to under baking or improper cooling (*ad hoc* definition).

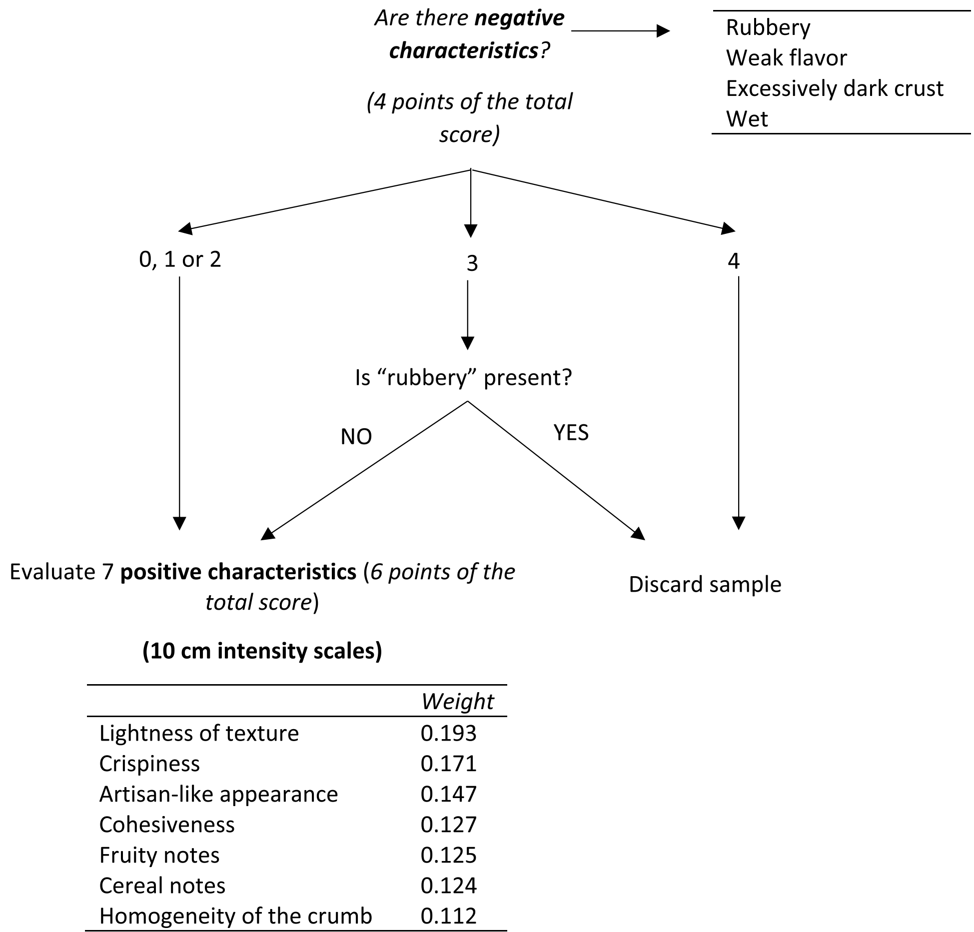

Fig. 5. Proposal of a decision tree for sensory quality evaluation of gluten-free breads, based on results from CATA analysis and regression tree analysis.

3.5. Proposal of an approach to evaluate quality of gluten-free bread

Bringing together the results obtained in this study, key descriptors influencing the acceptability of GFB were identified using data from CATA analysis and regression trees. Descriptors common to both analyses were identified and similar or opposing terms were consolidated. This process considered the effects on mean acceptability of the CATA descriptors and the significance of the regression tree nodes, including size and variation in acceptability influenced by the presence or absence of each descriptor. Identified key positive and negative descriptors were grouped as shown in Table 2 along with the definition of each term. Definitions are based on the information from various authors, adapted to the context of bread and discussed and agreed within the research group.

Based on these key descriptors, we propose a decision tree of GFB (Fig. 5). This evaluation-tool would assess negative characteristics signaling their presence or absence and positive attributes through intensity scales. Taking into account the impact on mean acceptability of each descriptor, if a bread exhibits all four negative characteristics, it would not be considered an acceptable product. However, they do not weight equally: "rubbery" had a greater impact than the others (effect on the mean = −1310/ weight=0.329). Thus, a product with three of them may still be acceptable if "rubbery" is absent, depending on the positive attributes. The weight of each positive attribute must be considered when estimating the final acceptability of the GF. In Fig. 5, the names of the scales replace the original descriptors, as the seven key positive descriptors selected must be converted into scales, ensuring that their endpoints directly reflect the key attributes. If the evaluation of negative characteristics is acceptable and positive descriptors score 6 out of 10 or higher, the product could be concluded to have a suitable sensory characteristics and possibly have good acceptance by consumers. This approach balances negative and positive characteristics and could be a useful tool for quality evaluation by manufacturers, as it follows consumers' acceptability criteria.

3.6. Limitations of the study

Control sample, without APP and flaxseed, was not considered for this consumer trial and this makes it difficult to achieve clear conclusions about the effect of flaxseed attending to the results described in this consumer trial, which only concluded those samples most highly rated in the preliminary sensory assessment.

In the future, it would be desirable to replicate this analysis with a larger variety of samples, including commercial GFB, to develop a more comprehensive decision tree. Additionally, in this study, appearance and its acceptability, as well as texture and flavor with their respective acceptability, were evaluated separately. If these aspects were assessed together along with overall acceptability, a single regression tree could be proposed.

4. Conclusions

This study suggests that it is feasible to use a blend of upcycled apple pomace powder and local flaxseed, to create appealing products for consumer, aligned with the growing demand for sustainable food production practices.

i. The samples with the highest acceptance and more relation with the key positive characteristics were the ones containing 12 % flaxseed and up to 6 % APP. Considering the samples studied, the optimal formulation would be A6F12, which balances both key ingredients effectively.
ii. Although gluten-free feature is the focus of this work, this could be a bread aimed at all the population, because the acceptance wasn't influenced by consumption patterns. However, there were differences in the evaluation criteria between groups: usual gluten-free consumers considered a broader range of attributes when evaluating the overall liking of the bread, compared to consumers not familiarized with gluten-free products. Both usual consumers of gluten-free bread and those from general population shared similar preferences regarding bread, but the current market does not offer gluten-free options that match gluten-containing ones in quality or price. This gap between demand and supply suggests an opportunity to continue improving accessibility and developing products that meet the needs and requirements of celiac consumers, reducing the disparity in the consumption experience between them and general population.
iii. This study highlights the importance of conducting sensory evaluations with both gluten- and non-gluten consumers, in order to ensure that the products developed meet the expectations, which is crucial given the increasing popularity of gluten-free diet. Additionally, if gluten-free products would be generally accepted by not diet-restricted sectors as well, this would help to erase the social distress suffered by those who necessarily have to adapt their diet.
iv. Additionally, a decision tree is proposed for sensory assessment of gluten-free breads, based on key descriptors identified in the study with consumers. This tool sets the bases for a standard method of analysis which should be further validated, including control samples.

Ethics statement

The authors declare that this study was conducted in accordance with the fundamental ethical principles of scientific research. All procedures performed in this study comply with the ethical standards of the institution of origin and with the 1975 Declaration of Helsinki, revised in 2013.

- Written informed consent was obtained from all human participants involved in the study.
- The research protocol was approved by ethics committee of the University of the Basque Country (approval number: M10_2023_054).
- The authors declare that there are no conflicts of interest that could have influenced the results or interpretation of the data presented.

CRediT authorship contribution statement

Leire Cantero-Ruiz de Eguino: Writing – original draft, Investigation, Formal analysis, Data curation. **Jesús Salmerón:** Supervision, Investigation, Conceptualization. **Monica Ojeda:** Resources. **Francisco José Perez-Elortondo:** Writing – review & editing, Resources, Methodology, Conceptualization. **Iñaki Etaio:** Writing – review & editing, Methodology, Formal analysis. **Edurne Simón:** Resources, Funding acquisition. **Jonatan Miranda:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Olaia Martinez:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2025.100696.

Data availability

Data will be made available on request.

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