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Oral processing of bakery products: An overview of current status and future outlook

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ABSTRACT

Food oral processing (FOP) is an emerging research topic that allows a better comprehension of the relation between intrinsic food factors (physicochemical and sensory properties), and human physiology and eating behaviours. FOP can then help in the design of novel and healthier food to meet both quality requirements and consumer needs. In this context, this review presents the current state of knowledge and new insights for future research concerning FOP of bakery products. The application of FOP in bakery science is new, with different protocols and related evaluation being applied, as detailed in this review. The current knowledge shows that bread structure and texture, influenced by formulation and process conditions, as well as the crust and shortenings present, impact bread breakdown and bolus formation, sensory perception, and food physiological effects such as glycaemic response, satiation, and satiety. For a better comprehension of oral processing, cross-modal perception between sensory attributes is used to understand consumer perception and this is carried out using both *in vivo,* and *in vitro* methods. This review highlighted the great potential of FOP to assist researchers and producers to face the current challenges relating to i – salt, fat and sugar reduction in bakery products to fulfil current food nutrition policies, ii – the design of healthier bakery products, and iii – the development of bakery products for consumers with special dietary requirements and ageing needs. In conclusion, FOP shows great potential to assist in the development of novel and healthier foods to meet actual food nutrition policies and consumer needs and should be more explored in bakery science and production.

1. Introduction

Over time, studies focusing on the transformation of food to bolus have emerged, to better understand the interaction of food attributes and the sensations caused in the oral cavity that generate brain signals involving eating behaviour that, in turn, reflect in the physiological well-being of individuals. Food oral processing (FOP) has emerged as an interesting area of research that evaluates food as it passes through the oral cavity (He et al., 2022). FOP begins with the first bite and is followed by mastication until a food bolus suitable for swallowing is obtained for the digestion and absorption of nutrients (Wang & Chen, 2017). The first research was carried out approximately two decades ago, relating the importance of oral processing to food science, nutrition, psychology, physiology, and neuroscience, among other areas, positioning it as an interdisciplinary research area (Chen, 2009; De Wijk et al., 2003; He et al., 2022).

FOP studies the alterations to the food structure by mastication, in relation to food physicochemical properties and focusing on how sensory attributes create a perception such as disgust for or satisfaction from the food (Puerta et al., 2021). In this process, understanding different types of consumers (with or without special needs), food matrices (liquid, solid, portion size, with or without spreads etc.), and targets (sensory, behavioural, nutritional etc) provides opportunities for the design of food formulations to improve the consumer experience (Devezeaux De Lavergne et al., 2021).

FOP has allowed the evaluation of eating behaviours associated with food sensory properties, such as texture that have been shown to influence consumer satiety (Devezeaux De Lavergne et al., 2021). In

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addition, oral processing, especially mastication process, has an important role in some feeding routine pathologies such as post-stroke dysphagia, obesity, tongue cancer, xerostomia and Down syndrome that affect the health of the consumer during the different stages of life (Moon et al., 2018; Schwartz et al., 2018; Tobberup et al., 2019).

FOP has studied different food matrices, including staple foods, like bakery products (BP), especially bread. Conventional wheat bread and its gluten-free version present a complex structure composed of crumb and crust. These characteristics leave a heterogeneous structure that can be evaluated by the study of mechanical behaviour during mastication and by studying other aspects of human physiology like glycaemic index (GI), satiety and satiation. Different challenges are faced in the formulation of these products, in this way oral processing is an interesting tool for evaluating the sensory properties of these formulations and the physiological effect after consumption (Gao & Zhou, 2021).

This comprehensive review presents the current state of knowledge and new insights for future research concerning FOP and related evaluation of bakery products. The review is structured with Section Two presenting a current panorama of research on FOP, which guides the discussion in the next sections. Section Three concentrates on the oral processing of bakery products, providing detailed information about protocols and related evaluation, as well as describing issues, advances, and challenges. Section Four gives the conclusions reached and suggestions for future research, highlighting the great potential of FOP to help food scientists and producers to face some of the current challenges related to bakery products to fulfil food nutrition policies and meet consumer needs.

2. Overview of research on FOP

In the last decade, the focus on the relation between food and the oral cavity has been gaining the interest of food scientists. Instrumental methods have been used to evaluate the physicochemical properties of food in parallel with FOP methods, complemented with sensory analysis and physiological measurement, to obtain a better understanding of food and oral processing interaction.

To present this overview of research on FOP, a bibliometric analysis was carried out. For that, the Elsevier Scopus database was explored using the following research keywords: “oral processing” AND “food”. Languages were restricted to English, French, Portuguese, and Spanish published until December 2023. The papers were screened by reading the title and abstract and by full-text reading and exclusion of the duplicated selected articles. The search resulted in 538 articles of which 469 met the inclusion criteria. Of these, 30 articles were regarding bakery products or bread. The inclusion criteria were “food oral processing evaluated *in vivo* or *in vitro* including bouche artificielle”. Exclusion criteria were “oral processing evaluated in animals” and “oral processing evaluation for dentistry purposes”. Fig. 1 provides a panorama of FOP research from the first publication in 2003 to 2023, showing the most-used keywords, arranged into five clusters. The largest cluster (in red) has 27 items related to the physicochemical and sensory properties of food such as particle size, lubrication, texture, adhesives, and hardness, involving the perception of gels, breads, meats, oil, fats, and starch products, which are the most-studied food matrices through oral processing. The second cluster (green) has 17 items, associated with different stages of life and consumer physiology in relation to caloric intake, appetite, satiety, satiation and feeding behaviour, which have an

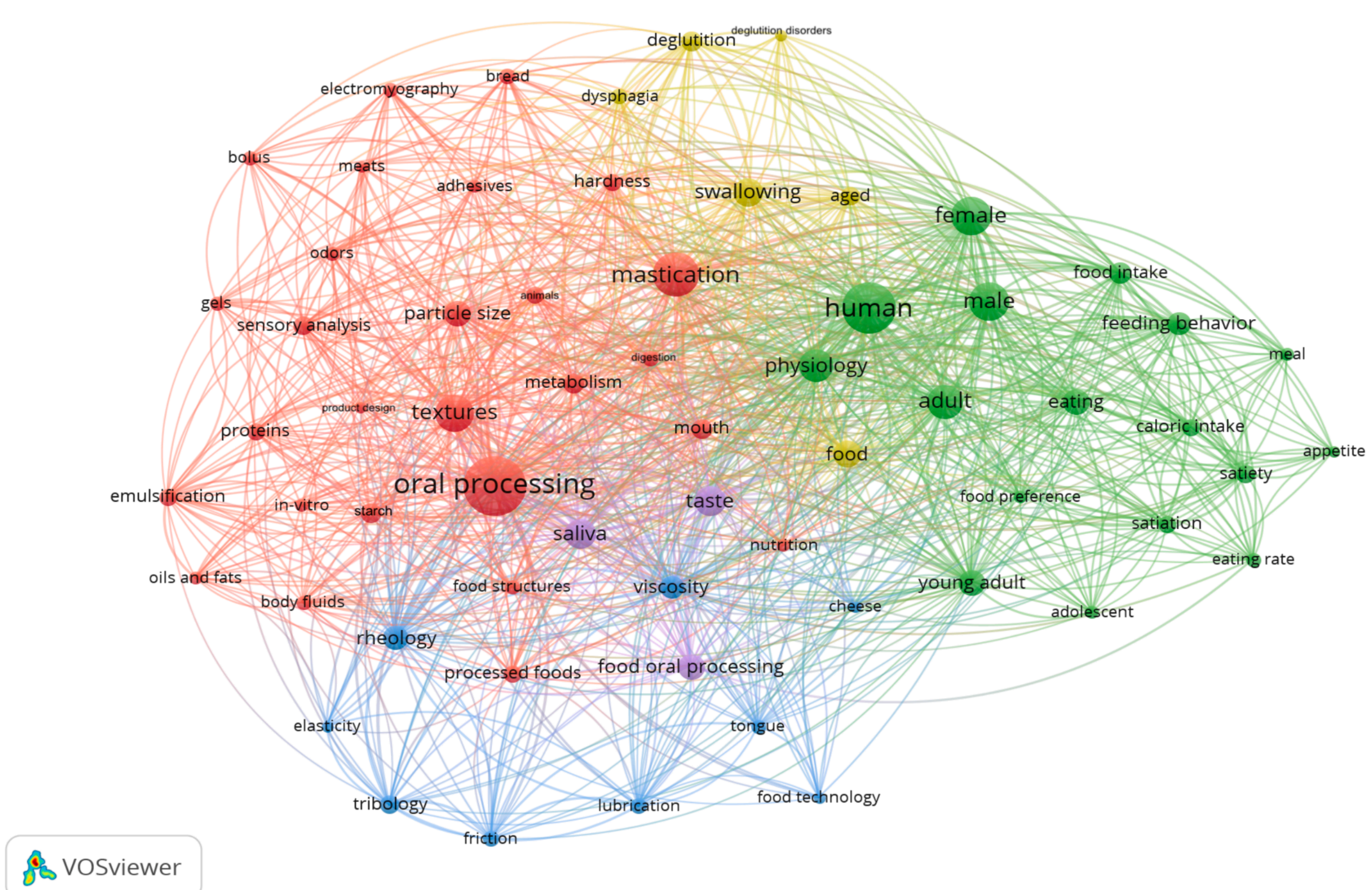

Fig. 1. Keyword co-occurrence network from articles about food oral processing. *Size of the bubbles represents more frequently used terms while thicker connectors correspond to more frequent co-occurrence of terms. Source: Scopus database (2003 - 2023). A total of 3,424 keywords integrate the evaluation, resulting in 62 linked items. A minimum of 15 occurrences was adopted to integrate keyword analysis using the VOSviewer software v1.6.19 (Leiden University, The Netherlands).

important role in consumer psychology. The third cluster (blue) has 9 items, linked to the rheology and tribology properties such as friction, lubrication, viscosity and elasticity. The fourth cluster (yellow) contains 6 items connecting food consumption with deglutition disorders, especially dysphagia, which can be affected in some stages of life or health conditions. The fifth cluster (purple) has 3 items representing taste attributes and the role of saliva in FOP.

The first publication occurred in 2003, evaluating the oral processing of semi-solid foods containing fats in different percentages to understand the sensory attributes during the intraoral manipulation of the samples (De Wijk et al., 2003). Following this publication, different food matrices were evaluated through *in vivo* and *in vitro* methods. Fig. 2 clearly shows that FOP is an emerging research topic, with more than 40 articles published annually in the last five years.

The papers show that FOP enables the interface between food science, nutrition, and health, thus providing answers related to consumer sensory perceptions, assisting in the development and reformulation of products with better sensory attributes for different types of consumers. FOP analysis integrates three research areas involving the physicochemical and sensory properties of food, its physiological effects, and consumer eating behaviour (Fig. 3). This figure exposes the importance of food properties for the bolus formation, mastication, and swallowing process. For deeper understanding, we consider it appropriate to read He et al. (2022) review, which presents detailed information about FOP and the principal concerns (physical, physiological, and psychological areas) of different food matrices.

This section has highlighted FOP as an emerging and interdisciplinary research topic that allows a better comprehension of the relation between food intrinsic factors, physicochemical properties, sensory perception, eating behaviour, food intake and its physiological effects.

3. Oral processing of bakery products

Bakery products, especially bread, are traditional staple foods frequently consumed around the world. Traditional white wheat bread is constantly being re-designed due to the interest in less salt, sugar and fat content and reduced glycaemic index (Gao & Zhou, 2021).To achieve these goals, different food ingredients are being tested. Besides the improvement of each bakery products nutritional profile, reaching consumer acceptance is an important factor. The evaluation of the complex structure of bakery products through oral processing can help to understand the sensory perceptions of consumers in the performance of these products, aligned with the consumer needs and nutrition policies (Chen, 2009).

The bibliometric map presented in Fig. 1 was fragmented to generate Fig. 4, which shows the most used keywords in the 30 articles related to bakery products oral processing. Fig. 4 is arranged into 3 clusters. The largest one (in red) relates bread texture to oral processing (mastication, saliva, bolus) and sensory perception. The second (in green) is related to taste and odour perception during FOP in humans and compound identification and quantification through instrumental analyses. The third cluster (in blue) highlights physiological effects relating to starch digestion and metabolism.

Regarding bakery products, only 'bread' appears as a frequent keyword since bread is the most investigated. Among the founded articles, 26 evaluated different types of wheat bread, 3 evaluated gluten-free (GF) bread and only one evaluated biscuit. Research on bakery products or bread oral processing has recently been conducted. The first article was published in 2014, and the highest number of publications was in 2019 as shown in Fig. 5.

Fig. 6 presents a timeline of research relating to bakery products oral processing, highlighting the main approaches. Through the years, the research has focused on the investigation of the effects of bread structure and texture (Gao et al., 2015; Panouillé et al., 2014), integrating the cross-modal perceptions of aroma and texture (Jourdren et al., 2017a,b) on consumer perception during bread oral processing. For that, the evaluation was carried out during and after the bolus formation using both *in vivo* and *in vitro* methods. The evaluation of satiation and satiety was also evaluated during the mastication process, in which starch degradation could have an impact conferred by texture (Gao et al., 2020; Nguyen et al., 2017).

In 2020, the first study evaluating FOP in commercial gluten-free bread (Puerta et al., 2020) was published and to date (December 2023) there are only 3 published investigations related to the structure and texture, FOP and gluten-free bread perception, with and without spreads (Mosca et al., 2022; Puerta et al., 2021). The most recent research focused on evaluating the salt level reduction on bread, aiming to fulfil food nutrition policies while keeping high consumer liking of this staple product (Faridi Esfanjani & Mohebbi, 2023).

Table S1 summarizes the 29 research articles regarding oral processing of bakery products describing: 1- aim of the study, 2- sample characteristics, 3- oral processing, considering sample presentation and

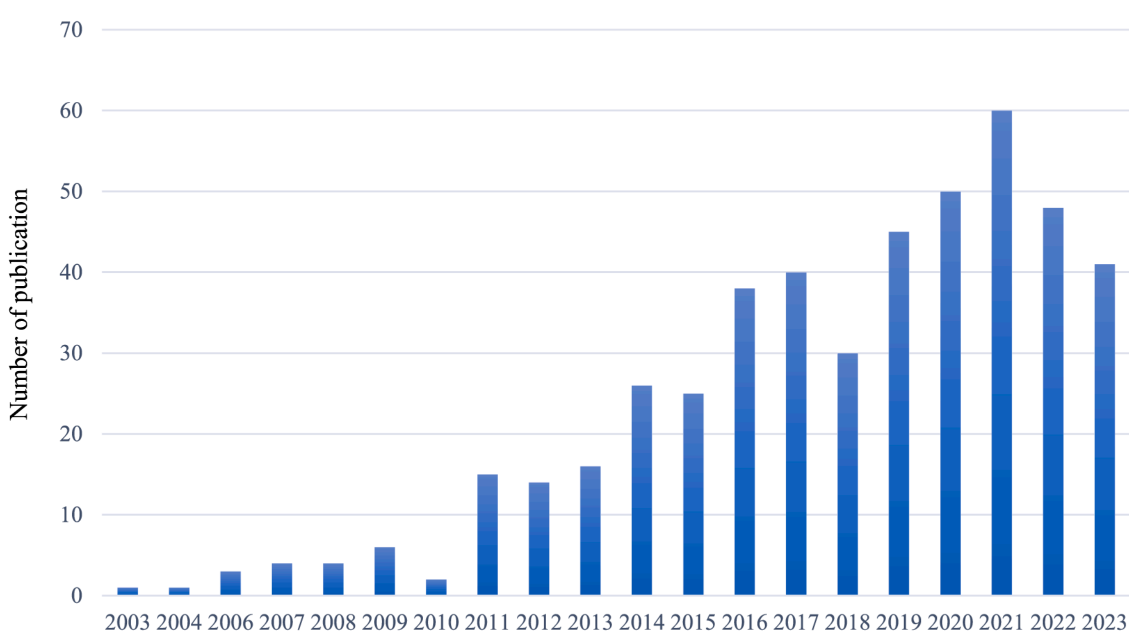

Fig. 2. Annual scientific articles of FOP production.

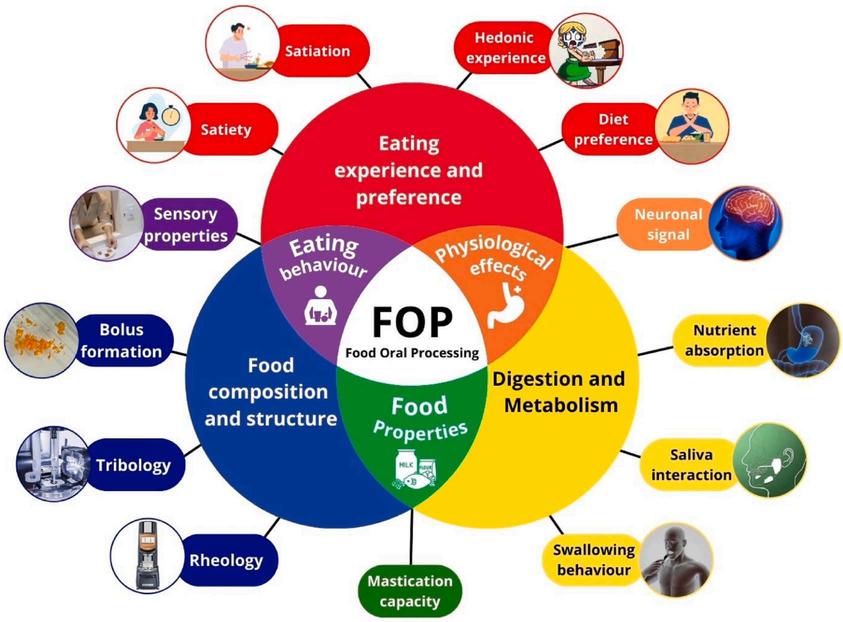

Fig. 3. The three most studied areas of FOP that assess the physicochemical properties of foods, oral physiology and eating behaviour of the consumer. Each one of these areas encompasses subareas with different research approaches that are interlinked with one another.

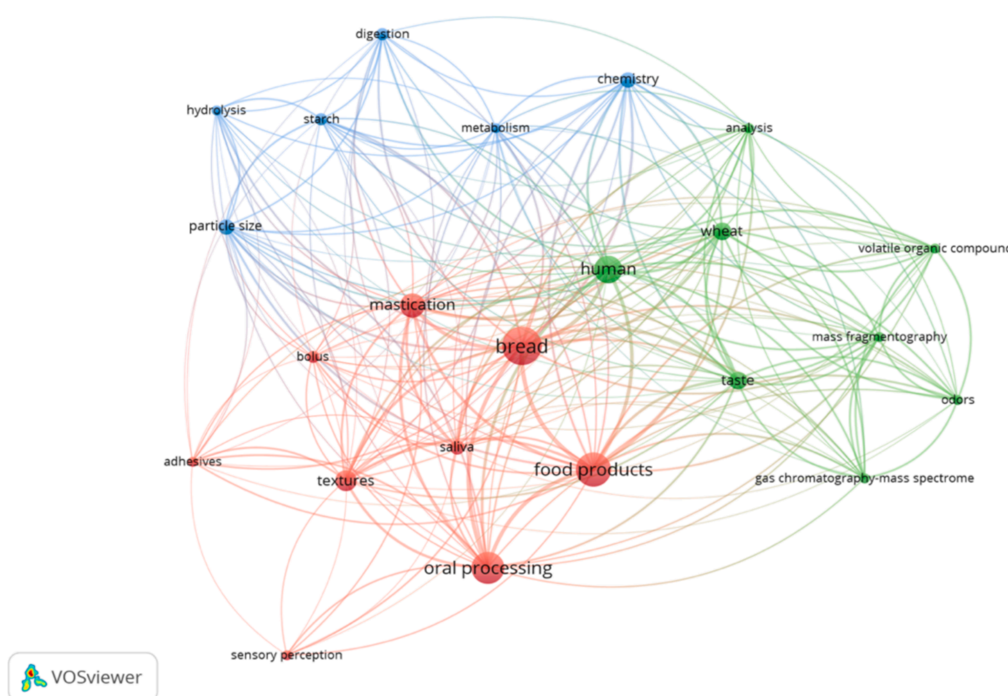

Fig. 4. Keyword co-occurrence network from articles on bakery products oral processing. *Size of the bubbles represents more frequently used terms while thicker connectors correspond to more frequent co-occurrence of terms. Source: Scopus database. A total of 453 keywords integrate the evaluation, resulting in 23 linked items. A minimum of 5 occurrences of the keywords found in the 29 retrieved articles (published between 2014 – 2023) was adopted to integrate the keyword analysis using the VOSviewer software v1.6.19 (Leiden University, The Netherlands).

serving size, participants characteristics, mastication behaviour and the bolus formation parameters evaluated, 4- related analyses, such as bread physicochemical composition, nutrient composition and sensory evaluation; assessment of masticatory cycles, oral volume and saliva properties; health-related properties, 5- main findings.

Of the 29 articles, 6 articles evaluate the oral processing of bread in parallel with the structural properties, 18 articles evaluate the oral processing, structural and sensory properties of bread, 3 articles implemented *in-vitro* methods and 2 articles evaluated the behaviour and preferences of the consumers. At the beginning, the focus of oral processing was on evaluating the structure of breads that were generally formulated with wheat and rye flour while, in the last couple of years, research has also included gluten-free bread formulations and the investigation of different breadmaking processes such as steaming, baking conditions and sourdough fermentation.

Table S1 shows the parameters evaluated with more frequency in the

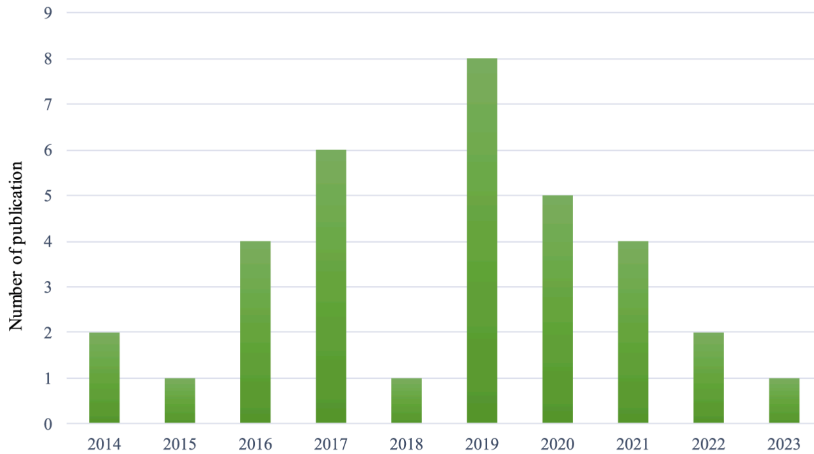

Fig. 5. Annual production of scientific articles about bakery products or bread oral processing.

Fig. 6. Timeline of publications regarding oral processing of bakery products, from the first publication in 2014 to 2023.

oral processing of bread, which were masticatory efficiency, particle size distribution, bite force, oral cavity volume, consumption weight, sodium release, mastication, and swallowing time. Bread portion sizes ranged from 2 g to 7 g (with or without crust) and were masticated until the formation of the food bolus that was then collected, between 3 and 18 s or from 3 to 20 masticatory cycles. The panellist was a reduced group of consumers, between 5 and 80 participants, all these participants had good dental status, permanent dentition, normal occlusion, none had periodontal disease, no pain, no rhinitis, no piercing, and no smokers. In some studies, the participants were not trained, and, in others, panellists were previously trained (Gao et al., 2017; Jourdren et al., 2016b; Panouillé et al., 2014; Pu et al., 2021b).

In parallel with oral processing, instrumental analyses such Texture Analysis (TPA and others), volscan profile, image analyses, EMG and masticator simulation were used to evaluate the bread structure and texture. Proton-transfer-reaction mass spectrometry (PTR-MS), gas chromatography-mass spectrometry (GC–MS) and HPLC were used to evaluate the volatile compounds. Sensory methods such as TI, TDS, CATA, DA, QDA and D-QDA were used to evaluate sensory attributes of texture, flavour, odour, and aroma. Recent studies like Gao et al. (2019) and Aleixandre et al. (2019) incorporated *in-vitro* analysis using the INFOGEST protocol to evaluate starch hydrolysis and determine the glucose equivalent.

Studies have focused on the evaluation of one sensory attribute of bread during oral processing, i.e., texture, taste, flavour, odour, or aroma. Until now, no cross-modal perception of sensory attributes of bakery products has been reported, which is an important gap for future research to assess the effects of adding or reducing ingredients (like salt, sugar, and fat) and the effects of storage time on bakery products sensory perception.

Bread is the most consumed bakery product and, consequently the most researched among this area. The review found only one study of biscuits, conducted by Le Révérend et al. (2016). These authors evaluated oral processing in three different biscuits and eating behaviour during their mastication compared with cereals and granola bars, evaluated through EMG and Kinematics of Jaw Movements (KMJ), showing that the difference in structure can influence the breakdown during oral processing (Le Révérend et al. 2016). These results suggest that mastication behaviour can be influenced by changes in biscuit texture and indicate the importance of the oral processing evaluation in other types of bakery products apart from bread, such as biscuits, cakes, pizzas, bagel, muffins and others. Due to global health concerns, it becomes imperative to (re)design bread products with reduced glycaemic index, lower salt, sugar and fat content and maintain consumer acceptability. This requires an in-depth understanding of the physics of the transformation of bread to bolus as well as the sensory perception of consumers. This article provides a critical review of bread oral processing, from ingestion to perception. The structural property-oral processing relationship is the key to understanding sensory perception in relation to bread characteristics and oral physiology. The significance of bread heterogeneity and changes in mastication ability, especially the contrast between bread crust and crumb and, also, ageing conditions, are highlighted.

The following subsections have been organized by topic, providing information about methods, advances, challenges and new insights for future research concerning the oral processing of bakery products.

3.1. Relation between bread structure, texture and oral processing

The articles, presented in Table S1, reported the evaluation of oral processing in different type of bread such as baguette, toast, western baked, oriental steamed, chunshu and sourdough to understand the relation between the structure, oral processing and consumer perception.

There are different factors that determine the structure of bread, such as the ingredients used in the formulation (especially those that contain starch), the fermentation process, the degree of hydration, the preparation of the dough and the cooking conditions (Aleixandre et al., 2019). The final morphologies of bread, such as the presence of crust and crumb, and the size, shape, and distribution of cells, lead to different mastication behaviours in terms of structure perception and digestion, which are particularly important to the mastication process (Gao et al., 2015).

Bread was evaluated with and without crust, as shown in Table S1, 9 articles evaluated just the crumb and 18 evaluated the crumb and crust together (2 articles did not report the type of bread sample). The evaluation of the crumb and crust together shows a greater number of mastication for formation of a cohesive food bolus, as well as influencing the release of aromas when compared to bread crumb alone (Jourdren et al., 2017a; Mathieu et al., 2016).

During day-to-day consumption, bread is a common carrier food frequently eaten with spreads such as butter and cream cheese. This can affect the oral processing, showing that spreads can help in the bolus formation increasing the lubrication and, in consequence, the modification of bolus particle size, the dynamic sensory perception and the oral processing behaviour (OPB) (Van Eck et al., 2020; Mosca et al., 2022).

The rheological properties of the bolus are influenced by the structure and texture of the bakery products, modifying the number of mastication, the absorption of saliva and, consequently, the contact with alpha-amylase (Panouillé et al., 2014). Regarding the flavour-conferring ingredients such as salt, sugar, or polyols, they were shown to have an interaction forming hydrogen bond between starch chains in the amorphous regions in starch granules helping to the stabilization of the dough in consequence texture and flavour release are modified (Ding & Yang, 2021; Faridi Esfanjani & Mohebbi, 2023).

3.2. Assessing bread sensory perception during oral processing

Sensory methods in parallel with the evaluation of oral processing parameters are used in 18 of the 29 articles regarding FOP and bread (Table S1). The most frequently descriptive sensory methods applied were TDS, TI, PP, DA, QDA, D-QDA, and CATA to obtain information about attributes like texture, taste and aroma. These methods were applied at the same time, with FOP used to collect the bolus sample for other analyses like mechanical properties, and physiological measurements (Gao et al., 2017; Jourdren et al., 2016b; Panouillé et al., 2014).

At the beginning of oral processing in bakery products (2014), the evaluation of the texture was the principal interest but, after three years, Jourdren et al. (2017a, b) investigated the influence of bread structure, volatile compounds and aroma perception using PP and TDS while Pu et al. (2019a,b, 2020) evaluated the aroma release and volatile compounds through TDS and QDA. Pu et al. (2021b) evaluated, for the first time, the taste compounds released and their perception using TDS and QDA. These examples show the evolution of the joint application of sensory analysis and FOP to bakery products.

Texture is one of most studied attributes and is closely related to oral processing (Panouillé et al., 2014; Pu et al., 2021a). It is a dynamic perception and appears from the continuous sensing of the changes in food properties through the oral cavity receptors and the force of the mandibles (Gao et al., 2017; Nishinari et al., 2023). Aspects such as the ingredients and the baking conditions can modify the texture and, in consequence, the mastication process. Panouillé et al. (2014) evaluated three kinds of wheat bread with different hydration levels and showed that the panellists exhibited different masticatory behaviours regarding the kinetics of bolus formation and the final bolus properties. Jourdren, et al. (2016a) also showed the importance of hydration and evaluated some texture attributes such as “soft”, “dry”, “doughy” and “sticky”. Jourdren et al. (2016b) evaluated the influence of crumb and crust in breakdown pathways showing the presence of crust modified the oral processing behaviour, increasing the heterogeneity of particle size.

Flavour is a key attribute for consumer acceptance; for this attribute, saliva plays an important role during the flavour perception because it can control the transport of taste and aroma molecules to their receptors and the adsorption onto the mouth surfaces, having an interaction with the mucosa of the oral and nasal cavity (Avila-Sierra et al., 2024). Cross modal investigation has shown that taste compounds play an important role in aroma perception during FOP. Some primary compounds which affect the taste of the bread are salt and lactic acid. TDS was used to evaluate chunshu white bread and showed that the most dominant tastes were “sour”, “salty” and “sweet” (Pu et al., 2021b). These attributes can be modified by the food formulation, and it is important to analyse them through consumer tests to understand the perception of them.

Among different physical, chemical and sensory properties, aroma is another key factor for the acceptability of bread. The concentration of the aroma compounds in the retronasal cavity is significantly lower than the aroma released in the mouth cavity. The evaluation of volatile release of white bread through GC-IMS reported 35 volatile compounds. In relation to the perception of aroma, the most frequently indicated were “fermentation-like”, “flour-like”, “sweet”, “creamy” and “toasty”. This result helps the understanding of aroma release and aroma perception in food consumption to create better white bread (Pu et al., 2020; Pu et al., 2019a).

As highlighted by Jourdren et al. (2017a, b), cross modal perception of sensory attributes of bakery products offers benefits to the dynamic sensory perception of the consumer during oral processing, which have not yet been explored in relation to different bakery products. Novel studies should explore texture-odour-taste–aroma interaction to provide valuable information to assist the development of different bakery products formulations.

3.3. Saliva and starch hydrolysis and oral processing of bread

Saliva facilitates FOP, thereby lubricating food during bolus formation and generating enzymes that break down substances, such as starch present in bread formulations (Avila-Sierra et al., 2024).The starch hydrolysis of bread can be modified by its composition and microstructure, having an influence in saliva secretion and impregnation during the formation of food bolus. These interactions subject food to enzymatic breakdown by saliva alpha-amylase, which gradually increases the adhesiveness force of the bread bolus during oral processing through starch hydrolysis (Pu et al., 2024). Starch hydrolysis has an impact on blood glucose (Joubert et al., 2017). For this reason, several researchers have focused their work on the evaluation of bread structure and saliva interaction and digestion through *in vivo* or *in vitro* analyses (Gao et al., 20129; Gao et al., 2020; Aleixandre et al., 2019).

In relation to the physicochemical properties, the food hydration with saliva can affect the kinetics of starch hydrolysis by influencing the high porosity, the capillary action of the crumb structure and the degradation of starch during mastication (Jourdren, et al., 2016a; Mathieu et al., 2016). The presence of crust and hydration can alter the texture and sensory aspect that is dominant during mastication (Jourdren et al., 2016b; Pu et al., 2021a).

Some *in vitro* analyses were used to evaluate the gastrointestinal digestion of bread using the INFOGEST protocol to evaluate starch digestibility, showing the important role of structure in the transformation during oral processing (Aleixandre et al., 2019; Gao et al., 2019, 2020). The evaluation of a French baguette using an Artificial Masticatory Advanced Machine (AM^2 masticator) demonstrated the importance of saliva quantity in relation to the particle size distribution and fluid content of the bread bolus during the swallowing process (Avila-Sierra et al., 2024).

Pu et al. (2024) used electronic tongue, on-line mass spectrometry, and molecular docking to evaluate flavour perception. Their results showed the main interaction between flavour compounds and saliva, indicating the importance of saliva in oral processing. Future research should evaluate the influence of saliva interactions and starch hydrolysis on bread structures of different types, oral processing, and blood glucose alterations in products with reduced glycaemic index.

3.4. Oral processing to assist sodium, sugar and fat reduction of bakery products

Staple products, like bakery products, can contribute to an important consumption of critical nutrients related to chronic non-communicable diseases, like obesity, diabetes, and hypertension. Thus, there is a need to re-design bakery products to fulfil current food nutrition policies (Panouillé et al., 2014), like front-of-package warning labelling. Some studies have been developed and aimed at reducing the levels of salt in bread while maintaining bakery products consumer liking. Different strategies have been suggested for sodium reduction, such as a decrease in any added sodium, the use of taste enhancers or salt replacers and the addition of sourdough to bakery goods (Silow et al., 2016).

In this context, some studies have focused on evaluating the perception of the different percentages of salt in bread. Panouillé et al. (2014) evaluated the dynamics of salty and texture perceptions during oral processing of bread, showing that both were largely influenced by bread structure. Tournier et al. (2014) evaluated the salt release during bread consumption, measuring sodium content in saliva, showing that the sodium released increased when mastication muscle activity increased. Faridi Esfanjani, & Mohebbi (2023) evaluated the aroma-taste-texture interaction reducing the NaCl level of bread by 50 % using gel emulsifier, cheddar cheese aroma and monosodium glutamate showing that using the aroma-taste-texture interaction was an appropriate strategy to improve sensory properties of low-salt breads. This research demonstrated a different method in assisting with the reduction of sodium and how this change can be perceived through oral processing showing consumer acceptance or rejection of formulation.

Sweet bakery products reformulation is another challenge for the industry due to the need to reduce added sugar intake. Some reformulations are trying to use less sucrose and more low-calorie carbohydrate substitutes, such as polyol substitutes and sweetener substitutes (Luo et al., 2019). However, all these strategies can modify the structure, taste, odour, and aroma of the bakery products and, in consequence, the consumer perception (Sahin et al., 2019). For this reason, evaluation through oral processing can help the understanding of cross-modal interaction between all sensory attributes and some physiological and psychological aspects. To the best of our knowledge, there are published articles evaluating sugar reduction strategies for bakery products but none of these are integrating oral processing with analysis of the formulation. Thus, a promising approach to assist both food scientist and producers to reduce sugar content of cake and biscuits products is to investigate the effects of oral processing on the sensory perception of bakery products. Cross modal perception of sensory attributes of bakery products is important since those ingredients (salt, sugar, and fat) influence sensory perception and physiological responses of bakery products consumers.

In bakery products formulations, fats and oils, such as butter, margarine, shortening and vegetable oils, are used in different proportions. The role of these ingredients is to enable acceptable structure and flavouring and to facilitate the absorption of fat-soluble vitamins. The reduction of these ingredients is a challenge for the bakery products industry because high quality must be maintained while formulating healthy bakery products. The recent research of Mohammad et al. (2024) used encapsulation technology with fenugreek oil to mask its undesirable flavour and reduce the fat content. Su et al., (2023) used ovalbumin–ferulic acid–κ-carrageenan Pickering emulsion as a butter replacement. Both studies evaluated the attributes of bread formulation by sensory analysis but did not use oral processing. Due to the importance of this theme to the areas of food science, nutrition and public health, novel studies should include oral processing methods together with physicochemical and sensory analysis to assess the effects of fat reduction on bakery products.

3.5. Oral processing to assist improvement of the quality of gluten-free bakery products

Wheat gluten is a key structure-building protein, essential in leavened baked goods, and its central role in breadmaking and bread quality is until now irreplaceable. The absence of gluten has a great impact on the dough, the breadmaking process and final quality of the bread (Gasparre & Rosell, 2023).Thus, obtaining high-quality gluten-free (GF) bakery products continues to be a huge challenge for food scientists and producers, especially with an increasing need due to the growing number of individuals following a gluten-free diet. Gluten-free bread is the most sought-after and consumed gluten-free product among celiac and non-celiac consumers. Despite recent scientific advances and the growth of the gluten-free market, important issues such as the improvement of the sensory and nutritional quality of gluten-free bread still need to be addressed to meet consumer needs and choices (Capriles et al., 2023). Gluten-free consumers rely on a widening range of healthier and tastier gluten-free foodstuffs to improve aspects of their diet, nutrition, health, and wellness. More research about the influence of the properties of these products and consumer perception is needed, making it possible to outline strategies for the improvement of gluten-free bakery products. In the light of this, knowing the structure, mechanical properties and in-mouth behaviour of gluten-free products can help show consumer behaviour and clarify the sensory perception, eating rate, satiation responses and food intake for the performance of the gluten-free products (Capriles et al., 2023).

Puerta et al. (2020) used TDS to evaluate the sensory experience during consumption of gluten-containing (GC) bread compared to commercial gluten-free bread. The most perceived attributes at the beginning of consumption for the commercial gluten-free bread were hard, soft, spongy, dry, crumbly, sandy, compact, and pasty, and the perception of the texture varied from the beginning to the end, reporting sensations of fragmentation, amount of saliva, cohesiveness of the bolus with a dominant sensation of adhesiveness at the end of consumption.

In follow-up work, Puerta et al. (2021) used TDS to evaluate four rice-based breads prepared with varying water hydration and fermentation time. At the beginning of the mastication, short fermentation breads were perceived as "compact", whereas long fermentation breads were perceived as "aerated". Both formulations were perceived as "sticky". The modification of some conditions like fermentation time can improve the texture perception during the consumption.

However, bread is often consumed in combination with other foods like spreads (e.g. butter, mayonnaise). Oral processing behaviour of gluten-free breads may vary when consumed with spreads, modifying the number of mastication and the formation of the food bolus. Mosca et al. (2022) investigated oral processing behaviour and texture sensations of gluten-free and gluten-containing breads with and without butter and mayonnaise using CATA methods. In these conditions, the gluten-free bread was easily fragmented during the mastication cycles and the formation of a cohesive bolus needed more time in the oral cavity.

The association of instrumental and sensory methods help to understand the importance of oral processing in gluten-free bakery products and highlight how different conditions of production or consumption can influence the sensory characteristics as perceived by the consumers. Future research could focus on the study of new ingredients such as whole flours, alternative proteins, different types of gluten-free bakery products, shelf life, evaluating in celiac and non-celiac participants to compare the perception of both consumers.

3.6. FOP and development of bakery products for consumers with special and ageing needs

In recent years, society has generated greater awareness about the inclusion of people with special needs. In that sense, food science has also begun to generate interest in the production of staple food for people who were born or developed a disability of the oral cavity. The understanding of this human variability has led to the emergence of food products and nutrition programs for people with special needs (Ross, 2023).

Older age and some diseases such as dysphagia and Down syndrome cause the loss of mastication and swallowing strength and, consequently, the appetite can be affected. In another sense, infants need exposure to a variety of flavours and textures which plays an important role in the development of healthy eating habits (Moon et al., 2018; Ross, 2023).

For this reason, sensory properties of staple foods, especially texture, become an important aspect and almost a therapy for the treatment of this group of consumers. Bakery products could be part of foods used for the nutritional therapy of consumers with special needs, which are usually based on semi-solid or liquid foods. Therefore, the oral processing of different types of bakery products by these consumers is a necessary and challenging area of study to create bakery products with sensory properties, especially textures, appropriated to the development, improvement, and maintenance at these stages of life or when pathologies affect the oral cavity. To the best of our knowledge, no studies regarding bakery products oral processing by consumers with special or ageing needs have been published, this being an important insight for future studies.

4. Topics for further research

The continuous improvement, the implementation of new food matrices and the implementation of different food preparation methods is a challenge for oral processing of bakery products, and this leaves the following future perspectives:

(1) The gap between sensory evaluation and instrumental analysis.

- *In vitro* (mastication simulator) or *in vivo* evaluation of the organs (tongue, teeth, muscles) that make up the oral cavity together or apart could provide valuable results for the understanding of sensory perception in consumers with some pathologies that affects these organs or that, due to age, have been losing skills during oral processing.
- The evaluation of different types of bakery products, using *in vitro* and *in vivo* methods under different conditions of FOP to understand the impact of mastication on sodium, fat and sugar in human biomarkers such as and glycaemic index or eating behaviours.

(2) Bakery food design by future techniques.

- Bakery products industry and science are constantly evolving for sustainable production and improving the nutritional profile. In this sense, the evaluation of 3D printing and new clean label and sustainable formulations seems to be the future of bakery products. Therefore, FOP needs to focus on the evaluation of these formulations to understand consumer perception and generate possible solutions to current problems.
- The assessment of other types of bakery products such as biscuits, crackers, cookies, cakes, muffins, bagel and pizza are necessary for the reformulation of this type of products with better nutritional and sensory properties.
- The evaluation of changes in the physicochemical and sensory aspects of bakery products during shelf life using FOP can help to better understand storage conditions and consumer perceptions.

(3) Sensory acceptance among different range of consumers

- Human perception of sensory attributes through the oral cavity is carried out jointly, so it would be interesting to evaluate cross-modal interactions of texture, taste, odour, and aroma at the same time during the oral processing of bakery products.
- Flavour perception and saliva interactions are important aspects of sensory perception in bread; the evaluation of salivary flow can help identify the needs of special groups during mastication.
- The impact of non-sensory aspects on the oral processing of bakery products must be evaluated for a better understanding of consumer perception. In this way, strategies could be created that generate the perception of pleasant and healthy bakery products through non-sensory attributes in foods with greater nutritional value and with improved sensory properties.
- Studies of sensory properties of BP with people in different stages of life, ethnic groups or some pathologies involving the oral cavity are necessary for better representation of FOP consumer perception, and different range of consumers.

5. Conclusions

FOP is an emerging interdisciplinary research topic that investigates the interface between food science, nutrition, and health. FOP research highlights the interconnection between food physicochemical-sensory properties and human physiology and eating behaviours. This interdisciplinary approach can help in the design of novel and healthier food to meet actual food nutrition policies and consumer needs and should be more explored in bakery science and production.

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CRediT authorship contribution statement

Marión Elizabeth Aguilar Fernández: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Etiene Valéria de Aguiar:** Writing – review & editing, Methodology, Data curation. **Ana Carolina Conti:** Writing – review & editing, Supervision, Conceptualization. **Vanessa Dias Capriles:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, 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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2024.115044.

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