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Sodium reduction in biscuits using 3d printing for heterogeneous salt distribution

Redução de Sódio em biscoitos usando impressão 3d para distribuição heterogênea de sal

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ABSTRACT: This study investigated the sodium reduction through non-homogeneous salt distribution in 3D-printed cookies, focusing on consumer perception and product characteristics. Three formulations were developed: a control (C) and two reduced-sodium samples with homogeneous (75H) and non-homogeneous (75NH) salt distribution, composed of oat flour, corn starch, xanthan gum, extra virgin olive oil, water, and salt. Physicochemical analyses revealed differences in moisture content and water activity, with higher salt reducing these values. No significant differences were found in ash content or color parameters. Texture analysis indicated that reduced-sodium samples had higher firmness, though fracturability did not correlate with consumer acceptance. Sensory analysis with 27 trained tasters showed no significant differences in perceived saltiness between the reduced-sodium samples and the control, attributed to uniform salt perception during chewing and possible redistribution during baking. The findings suggest that 3D printing non-homogeneous salt distribution does not significantly affect perceived saltiness, although texture remains crucial for consumer acceptance. Future research should investigate greater sodium reductions, assess salt distribution pre- and post-baking, and include sensory evaluations with untrained tasters to better understand consumer acceptance.

Keywords: Salt reduction; Food printing; Salt intensity; Sensory analysis.

RESUMO: Este estudo investigou a redução de sódio por meio da distribuição não homogênea de sal em biscoitos impressos em 3D, com foco na percepção do consumidor e nas características do produto. Foram desenvolvidas três formulações: uma amostra controle (C) e duas amostras com teor reduzido de sódio e distribuição de sal homogênea (75H) e não homogênea (75NH), compostas por farinha de aveia, amido de milho, goma xantana, azeite de oliva extra virgem, água e sal. As análises físico-químicas revelaram diferenças no teor de umidade e na atividade de água, sendo que o maior teor de sal reduziu esses valores. Não foram encontradas diferenças significativas no teor de cinzas ou nos parâmetros de cor. A análise de textura indicou que as amostras com teor reduzido de sódio apresentavam maior firmeza, embora a fraturabilidade não se correlacionasse com a aceitação do consumidor. A análise sensorial com 27 provadores treinados não mostrou diferenças significativas na percepção de salinidade entre as amostras com teor reduzido de sódio e o controle, atribuída à percepção uniforme do sal durante a mastigação e possível redistribuição durante o cozimento. As descobertas sugerem que a distribuição não homogênea do sal na impressão 3D não afeta significativamente a percepção do sabor salgado, embora a textura continue crucial para a aceitação do consumidor. Pesquisas futuras deverão investigar maiores

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reduções de sódio, avaliar a distribuição de sal antes e depois do cozimento e incluir avaliações sensoriais com provadores não treinados para melhor compreender a aceitação do consumidor.

Palavras-chave: Redução de sal; Impressão de alimentos; Intensidade de sal; Análise sensorial.

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1 INTRODUCTION

Salt (sodium chloride) is a vital source of the essential micronutrient sodium and is one of the most extensively utilized condiments in home cooking and the food industry. It is well-documented that a diet high in sodium is associated with increased mortality and the incidence of cardiovascular diseases (CVDs), including hypertension and coronary artery diseases (Sun *et al.*, 2021; Buyukkestelli; El, 2019; World Health Organization, 2012). Cardiovascular disease is considered the leading cause of diet-related mortality, accounting for approximately 10 million deaths and 207 million disability-adjusted life-years (DALYs), particularly prevalent in countries such as China, Japan, and Thailand (Afshin *et al.*., 2019). An expanding body of research indicates that excessive salt intake can compromise the immune system, leading to various autoimmune conditions such as autoimmune encephalomyelitis and lupus (Sun *et al.*, 2021; Buyukkestelli; EL, 2019). High salt consumption disrupts the gut microbiome, decreases the survival rate of Lactobacillus in the intestines, and contributes to hypertension; moreover, it promotes liver fibrosis by generating excessive reactive oxygen species (ROS) (SUN *et al.*, 2021; Buyukkestelli; El, 2019; World Health Organization, 2012).

Reducing salt intake across the entire population is crucial for enhancing public health. Consequently, international authorities such as the World Health Organization (2018) and World Action on Salt and Health (WASH) (He; Jenner; Macgregor, 2010) advocate for a significant reduction in salt consumption. However, achieving this reduction poses considerable challenges, as salt not only influences the flavor and texture of final food products but also plays a critical role in food processing and preservation (Kongstad; Giacalone, 2020; Guo *et al.*, 2022).

Recent advancements in reducing salt content in food products have been the focus of some review works, which reported various innovative strategies aimed at addressing both health concerns and consumer acceptance. To achieve the salt reduction in bakery products it was described the use of salt substitutes like potassium chloride, the development of salt crystals with modified shapes and sizes to enhance dissolution rates, and the incorporation of flavor enhancers to maintain palatability (Ferrari *et al.* 2022). The importance of optimizing salt distribution within food matrices has been emphasized, as well as leveraging the synergistic effects of combining different salt substitutes to achieve a balanced taste profile, besides the use of microencapsulation techniques to control salt release and enhance sensory attributes (Nurmilah *et al.* 2022). Last but not least, 3D printing technology has been studied to precisely control the spatial distribution of salt within food, allowing for customized saltiness profiles (Thorakkattu *et al.*, 2024; Cotabarren; De Salvo; Palla, 2023; Escalante-Aburto *et al.*, 2021; Baiano, 2020).

As a technique that constructs food items incrementally, layer by layer, 3D printing offers a novel approach for creating authentic food textures. This is achieved through the precise placement of texturing components, the capability to print multi-material products, and the engineering of intricate internal structures (Thorakkattu *et al.*, 2024; Cotabarren; De Salvo; Palla, 2023). Three-dimensional food printing (3DFP) is a promising market on a small or large scale and can replace various processing steps in industries or entire processes, reducing customization costs and human error while increasing efficiency and reliability (Escalante-Aburto *et al.*, 2021; BAIANO, 2020). Additionally, production can become on-demand, where food is produced only when requested, when sales are guaranteed, increasing working capital and reducing stock costs (Dankar *et al.*, 2018). An important issue concerns the sustainability of 3D food printing in terms of reduction of both resource consumption and food waste production. So much that 3D printing could be one of 12 technology platforms useful to develop sustainable urban food ecosystems as a response to the increasing world population and the limited availability of land, water, and energy (Baiano, 2020).

The interest in 3DFP has grown remarkably in the last decade due to the associated expectations of supply chain simplification, better use of existing food materials, food shelf-life extension, food design customization, and personalized nutrition (Thorakkattu *et al.*, 2024; Zhang *et al.*, 2022; Escalante-Aburto *et al.*, 2021). Personalized nutrition is one of the most exciting promises of 3DFP technology. It refers to a diet that can be applied to individuals or specific population groups, such as athletes, pregnant women, or older adults. An example of this application is the project "PERFORMANCE" (Development of Personalized Food using Rapid Manufacturing for the Nutrition of elderly consumers), which was founded by the European Union to develop and validate a holistic, personalized food supply chain for elderly persons with swallowing and/or masticating problems (Feng; Zhang; Bhandari, 2019).

In the past ten years, some authors have studied the 3D food printing for cookies and snacks, evaluating the influence of the technique on texture and product stability (Escalante-Aburto *et al.*, 2021; Baiano, 2020; Severini; Derossi; Azzollini, 2016; Lipton *et al.*, 2015). Meanwhile, non-homogeneous distribution by several approaches has been tested in food products to reduce sodium content (Kongstad; Giacalone, 2020; Guo *et al*, 2022). But only very recently there were the first reports on structuring food products by 3D printing as an approach to reduce its contents of sugar, salt, and fat (Cotabarren; De Salvo; Palla, 2023). Fahmy *et al.* (2021), for instance, investigated the formation of structured matrices by employing various layering designs of starch-based food materials with both regular and reduced salt content. Utilizing dual extrusion and integrated near-infrared heating, they developed a 3D printing method that enables precise control over texturing and the spatial distribution of sodium chloride. The study demonstrated that all printed structures, irrespective of salt localization variations, maintained consistent textural properties at identical infill levels. Moreover, the inhomogeneous spatial distribution of sodium chloride resulted in an intensified perception of saltiness. This discovery offered significant potential for creating reduced-salt products with enhanced flavor perception.

Considering all the above, the aim of this study was to investigate the reduction of sodium content through non-homogeneous salt distribution in different layers of 3D printed cookies, without causing significant changes in consumer perception and product characteristics, ensuring the feasibility of this technique.

2 MATERIAL E METHODS

2.1 RAW MATERIALS

The corn starch used in this work was obtained from a food industry in Maringa - PR and the oat flour was Quaker®. The corn starch, xanthan gum and extra virgin olive were obtained from Naturally Produtos Naturais.

2.2 BISCUITS PRINTING

Three biscuits formulations were developed for 3D printing: a control (C), and two samples with sodium reduction, namely homogeneous distribution of salt (75H) and heterogeneous distribution (75NH). The formulations were: 24 g of whole grain oat flour previously sieved (Bertel Metal Ind. ®, 710 mm, 25 mesh), 23.8 g of corn starch, 0.2 g of xanthan gum, 5.0 g of extra virgin olive oil, 46.0 g of water and fine salt in different quantities according to Table 1. Each formulation corresponded to approximately 30 biscuits of 3 grams each.

Table 1. Amount of salt in each formulation

	Layers 1 and 3	**Layer 2**
Control (C)	1.000 g	1.000 g
Reduced 25% in homogeneous salt (75H)	0.750 g	0.750 g
Reduced 25% in non-homogeneous salt (75NH)	1.125 g	0.000 g

All dry ingredients were previously mixed, then the liquid ingredients were added. After preparing the dough, it was left to rest for 15 minutes and then printed on the 3D food printer (Wiibox®, X1, Jiangsu, China) with a 1.5 mm output in three circular layers with a diameter of 20 mm. The biscuits were baked at 180°C for 25 minutes, cooled at room temperature (25°C) and vacuum packed. Figure 1 shows a printed biscuit with the use of dye in pre-tests performed to highlight the three layers in print. For all analyses, including the sensorial one, the dough was made with all the layers without dyes.

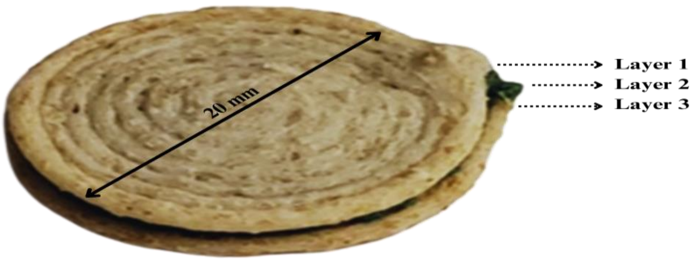

Figure 1. General aspects of the printed biscuit.
Source: photo by the author.

2.3 PHYSICOCHEMICAL ANALYSIS

The centesimal composition was characterized by moisture and ashes (AOAC, 2005). The colour was evaluated in a digital colourimeter (Minolta® CR 400), with readings of ten repetitions for each treatment. The results are expressed in the CIELAB system in L*, a* and b* values. The water activity was performed using the digital device AQUALAB® (4TE) at 25°C and the sodium content of the samples was assessed by flame atomic absorption spectrometry, according to AOAC (1995).

2.4 SENSORY ANALYSIS

The sensory analysis was performed with 27-trained tasters of both sexes ranging in age from 22 to 52 years, arranged in individual booths under white light. The tasters were trained in sensory analysis methods, and the analysis received approval by the research ethics committee of the State University of Maringa (CAAE 18718013.3.0000.0104). To check the difference in perception of salty taste among the samples, a control difference test was performed, which consisted by the presentation of the control sample (C) followed by the two samples with reduced salt content (75N and 75NH), coded with three random digits and in different positions to each taster, randomly (Monteiro; Cestari, 2013).

The tasters evaluated each sample about the control according to a structured 9-point scale (Table 2). They also performed an acceptance test comparing with the control, evaluating the samples concerning texture and salty intensity, according to a hedonic scale of 9 points, ranging from 1 (Extremely less salty than control) to 9 (Extremely saltier than control).

Table 2. Scale used to evaluate the intensity of the salty taste in the biscuits with different salt distributions

Scale	Intensity of salty taste
9	Extremely saltier than control
8	Much saltier than control
7	Moderately saltier than control
6	Slightly saltier than the control
5	Salty equals control
4	Slightly less salty than the control
3	Moderately less salty than the control
2	Much less salty than control
1	Extremely less salty than control

2.5 TEXTURE ANALYSIS

Texture analysis was performed at Texture Analyser TAXT2 Plus (Stable Micro Systems®, England), according to Berwig *et al.* (2017) and Garcia-Armenta *et al.* (2017). The 3-point bending rig probe (HDP/3PB) was used to evaluate the firmness and fracturability. The parameters used in the tests were: pre-test speed = 1.0 mm.s^{-1}; test speed = 1.0 mm.s^{-1}; post-test speed = 10.0 mm.s^{-1}; distance 2.0 mm and trigger 5 g.

2.6 STATISTICAL ANALYSIS

The physicochemical characteristics were performed in triplicates in each experiment repetition. In acceptability (sensory analysis) the experimental design consisted of randomized complete blocks (the treatments were the formulations and the blocks were the tasters). Data were submitted to analysis of variance (ANOVA) at 5% probability significance. The SAS Inst computer system (SAS Institute Inc., Cary, NC, USA, 2010) evaluated the differences between biscuits formulations and consumer acceptance.

3 RESULTS AND DISCUSSION

The variation in salt content between the formulations results on a difference in the moisture content (%) and water activity (Aw) of the samples, as can be observed in Table 3. The higher presence of salt reduces the moisture values (Noort *et al.*, 2010) and A_w (Kongstad; Giacalone, 2020), which could be confirmed through sample C.

Whereas ash contents showed significant differences among samples, colour parameters did not. The ash content may change due to sodium reduction in food, which could explain the verified reduction in sample 75H. An influence on colour would be expected due to salt reduction in the presence of sugars; however, as the formulations had o added sugar, no significant colour changes were observed (Bassett *et al.*, 2013; Belz; Ryan; Arendt, 2012).

Table 3. Physicochemical characteristics of the samples

	Sample C	**Sample 75H**	**Sample 75NH**
Moisture (%)	12.59^{a} ± 1.45	13.12^{ab} ± 0.17	14.88^{b} ± 0.28
Ash (%)	2.70^{a} ± 0.48	1.66^{b} ± 0.08	2.81^{ab} ± 1.39
Aw	0.46^{a} ± 0.00	0.58^{b} ± 0.01	0.51^{c} ± 0.02
Sodium content (mg Na/ 100g sample)	1103.6^{a} ± 9.70	829.6^{b} ± 13.50	818.4^{b} ± 22.70
L*	73.82^{a} ± 1.00	74.66^{a} ± 1.45	73.76^{a} ± 0.80
a*	2.56^{a} ± 0.20	2.49^{a} ± 0.28	2.63^{a} ± 0.10
b*	24.00^{a} ± 0.41	24.08^{a} ± 1.11	23.42^{a} ± 0.43
Firmness (g)	5461.00^{a} ± 2165	11176.00^{b} ± 2081	8001.00^{c} ± 2575
Fracturability (mm)	5.25^{a} ± 0.25	4.63^{b} ± 0.25	5.26^{a} ± 0.31

*Results are expressed as mean ± standard deviation (SD). Values with different letter in the same line are significantly different (p <0.05) by Tukey´s test. Source: research data.

Table 3 also presents the results of the sodium content. As expected, the control (C) showed a significant difference when compared with the samples 75H and 75NH (which did not show significant differences between each other), proving the 25% salt reduction performed.

The results for firmness and fracturability confirm the influence of texture on consumer acceptance. It can be seen that the samples with reduced sodium content (Table 4) showed higher values of firmness, i.e., the force required for food compression between the teeth is higher. On the other hand, it was not observed a direct relationship between fracturability and the biscuits acceptance for the different formulations.

Sensorially evaluating the samples with sodium reduction about the control, it was noticed that tasters had a similar perception (both for the homogeneous and heterogeneous distributions - Table 4), evaluating both samples on average as "slightly less salty than the control/saline equal to the control". The fact that no differences were evidenced in the perception of the salty taste between the different salt distributions may be related to the thin layers that formed the biscuits since during chewing it may not have caused any sensory contrast.

Table 4. Sensory analysis results

	Sample C	**Sample 75H**	**Sample 75NH**
Texture	5.00^{a} ± 1.31	6.20^{a} ± 1.94	6.62^{a} ± 2.03
Salty intensity	4.27^{a} ± 0.84	3.29^{a} ± 0.66	4.63^{a} ± 0.75

*Results are expressed as mean ± standard deviation (SD). Values with different letter in the same line are significantly different (p <0.05) by Tukey´s test. Source: research data.

During the baking stage, which took place after the biscuits were printed, a change in the salt gradient may also have occurred, since the different layers may have been dissolved and mixed. Despite the similarity in the evaluation of these two samples, consumers had good acceptance of the salty taste, even with a 25% reduction in the total amount of salt, and the proposed sodium reduction was not perceived.

The lower moisture content in the samples with salt reduction may have been an influencing factor in the texture negative evaluation, in addition to the food printing process itself, which may have caused significant effects on texture properties (Le Tohic *et al.*, 2018). Additionally, the baking may have resulted in unpleasant changes to texture (Dankar *et al.*, 2018). Anyhow, regarding texture sample 75H had a better score ("neither liked nor disliked") than the control (C) ("disliked moderately").

4 CONCLUSION

This study is one of the first contributions on 3D printing technology applied to achieve non-homogeneous distribution of salt for the purpose of reducing sodium content in salt biscuits, specifically targeting consumer perception of salinity. The findings revealed no significant differences in perceived saltiness between samples with homogeneous and non-homogeneous salt distribution. This outcome may be attributed to the thin biscuit layers, which likely resulted in uniform salt perception during chewing. Our results corroborate that texture plays a critical role in consumer acceptance and may influence sodium distribution.

Furthermore, the baking process following 3D printing may have caused the salt to redistribute more evenly across the layers, even in the non-homogeneous (75NH) sample. Future research should focus on investigating the impact of 3D printing on food texture and exploring non-homogeneous salt distribution across various food matrices. This includes assessing salt distribution before and after baking to understand the structural changes during processing.

Although trained tasters did not detect a significant sodium reduction, it would be valuable to conduct further studies with a greater sodium reduction and to include sensory analysis with untrained tasters to gauge the acceptance of the general consumer population. This approach would provide deeper insights into the feasibility of using 3D printing for sodium reduction while maintaining consumer satisfaction.

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