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CAKE FORTIFICATION WITH DIETARY FIBRE: IMPACT OF FIBRE INGREDIENTS IN A CAKE MODEL SYSTEM

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ABSTRACT

Despite its various health benefits, dietary fibre (DF) remains under-consumed, and many individuals fail to meet the recommended daily intake. Incorporating DF into wildly consumed foods while maintaining product quality is a significant challenge due to the negative impact on texture and sensory characteristics. Pound cake is a popular dessert in the Western world, however it is high in refined flour, sugar and fat; increasing the risk of type 2 diabetes, obesity, and cardiovascular disease. This study demonstrates the effect of different DF ingredients on the quality of cake and further investigates the concentrations at which resistant starch, pectin, β-glucan, cellulose and arabinoxylan can coexist. Response surface methodology resulted in the replacement of 38.45% flour by a optimal mixture of fibre ingredients. Evaluation of physicochemical characteristics including shelf life and sensory attributes showed that cake fortified with DF had a similar specific volume (-1.6%), a slightly harder crumb (+7.7%), but a prolonged shelf life (14 days) and an improved *in vitro* starch digestion profile than the control cake. Sensory results did not show a difference in the taste and hedonic attributes. This study provides information to progress in closing the fibre gap of foods without compromising consumer acceptability.

Keywords: Dietary Fibre, Cake, Response Surface Methodology, Sensory, Starch Digestion

1 INTRODUCTION

Baked cereal products represent a significant share of the market and encompass a diverse portfolio of products that vary in ingredients, processing methods, and shelf life. Within this category, cakes stand out as a popular segment, offering a wide range of formulations tailored to different consumer preferences and storage requirements (Jubayer et al., 2022; Mickiewicz and Britchenko, 2022). The global cake market is projected to reach USD $ 124.17 billion by 2030, of which USD $ 23.578 million is forecasted in Europe, growing at a compound annual growth rate of 4.03% from an estimated USD $ 101.91 billion in 2025 (Intelligence, 2025).

Cakes have a prominent place in global food culture (Grujić and Odžaković, 2021), serving as both indulgent treats and staple baked goods in many diets. However, while traditionally associated with pleasure and celebration, they are often perceived as unhealthy due to their high sugar and fat content and limited nutritional value. In response, recent advancements in food science have focused on reformulating cakes to improve their nutritional profile while maintaining their sensory appeal (Grujić and Odžaković, 2021; Mickiewicz and Britchenko, 2022). Reformulated cakes can serve as functional foods, addressing the dietary needs of specific populations, such as people with diabetes, while also offering broader health benefits to the general public. The psychology of dessert consumption plays a crucial role in dietary adherence and overall eating behaviour. Studies suggest that complete restriction of indulgent foods can lead to cravings, overeating, and reduced long-term adherence to healthy eating patterns (Stewart et al., 2022; Zhang et al., 2021). By incorporating controlled portions of nutritionally improved desserts into a balanced diet, consumers may experience satisfaction without feelings of deprivation, ultimately supporting healthier eating habits (Heidari et al., 2023; Shafiee et al., 2024).

Despite their widespread consumption, cakes and other baked goods often lack dietary fibre (DF), a key nutrient with well-documented health benefits. Adequate fibre intake has been linked to improved digestive health, better glycaemic control, and a reduced risk of non-communicable diseases such as cardiovascular disorders, obesity, and type 2 diabetes (Delzenne et al., 2024; O'Grady et al., 2019; Gill et al., 2021). However, global dietary patterns show that fibre consumption remains below recommended levels, underscoring the need for innovative food reformulation strategies (Stephen et al., 2017). Incorporating fibre into baked goods presents a promising approach to addressing this deficiency, yet it poses challenges in maintaining product quality and consumer acceptance. Fibres are known to disrupt the structure of baked products, often leading to undesirable changes in texture and sensory characteristics (Foschia et al., 2013; Gadallah et al., 2022). To date, most studies have focused on the individual addition of purified fibre ingredients to cake or similar bakery matrices (Aydogdu et al., 2018; Ceylan et al., 2021; Curutchet et al., 2021; Donkor-Boateng et al., 2024). In a recent study, Moradi et al. (2025) analysed the impact

of apple, potato and sugar beet fibres on a cake matrix. However, combining purified fibres that differ in origin, structure, and key properties (such as solubility, fermentability, and gelling capacity) offers the potential not only to enhance the nutritional profile of cakes but also to improve their technological performance. Such combinations may provide greater versatility in formulation, allowing better control of texture, moisture retention, and overall product quality.

The aim of this study was to develop a fibre-enriched white cake, with a mixture of purified fibre ingredients, which closely resembles a traditional white control cake, enhancing its nutritional value while maintaining consumer acceptability. By using purified fibre ingredients and a controlled formulation approach, the present study is able to more specifically assess the individual and combined impact of each fibre type on the physicochemical and sensory properties of the cake matrix. In addition, two distinct analytical methods for dietary fibre quantification (AOAC 991.43 and AOAC 2017.16) were compared to provide a more comprehensive and reliable assessment of the nutritional outcomes.

Response Surface Methodology (RSM) was used to evaluate the behaviour of five fibre ingredients (soluble arabinoxylan AgriFiber Soluble Fiber Corn (SFC), GENU® Pectin type BIG, PromOat® Beta Glucan, insoluble resistant starch Fibersym® RW starch, and cellulose VITACEL L 600-30) both individually and in combination within a cake system. These fibre ingredients were selected for their distinct properties to achieve a balanced impact on the food matrix, aiming for a broader spectrum of potential health benefits. Finally, the study evaluated the effects of the optimised fibre combination on the properties of the batter and the characteristics of the cake, including nutritional composition, sensory characteristics, and *in-vitro* starch digestibility.

2 MATERIALS AND METHODS

2.1 Raw materials

The ingredients used were biscuit flour (BF) (Odlums Group, Dublin, Ireland) (protein: 9.29 g/100 g and fibre: 6.16 g/100 g), fresh whole eggs (Clona Dairies, Clonakilty, Ireland), unsalted butter (Avonmore, Dublin, Ireland), granulated sugar (Siúcra, Dublin, Ireland), salt (Glacia British Salt Limited, Cheshire, UK) and baking powder (Dr. Oetker (UK), Leeds, UK). In the fibre-enriched cakes, part of the flour was replaced by purified DF ingredients, including water-soluble arabinoxylan from corn known as AgriFiber Soluble Fiber Corn (SFC) (AgriFiber Solutions, Mundelein, IL, USA) (protein: 5.48 ± 0.5 g/100 g and fibre: 45.96 ± 0.43 g/100 g), resistant starch type IV known as Fibersym® RW (MGP, Atchison, KS, USA) (protein: 0.07 ± 0.01 g/100 g and fibre: 47.86 ± 0.89 g/100 g), pectin from citrus known as GENU® pectin type BIG (CP Kelco, Atlanta, GA, USA) (protein: 0.72 ± 0.03 g/100 g and fibre: 45.19 ± 0.79 g/100 g), β-glucan from oat known as PromOat® Beta Glucan (Lantmännen Oats AB, Kimstad, Sweden)

(protein: 4.13 ± 0.09 g/100 g and fibre: 39.98 ± 0.04 g/100 g) and cellulose known as VITACEL L 600-30 (J. Rettenmaier & Söhne GmbH + Co KG, Rosenberg, Germany) (protein: 0.08 ± 0.02 g/100 g and fibre: 96.62 ± 1.22 g/100 g). To compensate for the reduced protein content, caused by the replacement of part of the biscuit flour with fibre ingredients, Viten® vital wheat gluten (Roquette, Lestrem, France) (protein: 76.74 ± 1.47 g/100 g) was added to the fibre-enriched cakes. The protein concentration of BF, DF ingredients and vital gluten was quantified following the Kjeldahl method (Kjeldahl, 1883). The fibre concentration of these ingredients was quantified by AOAC International (2022) method 2022.01.

All chemicals were purchased from Sigma Aldrich (St. Louis, MO, USA) unless otherwise stated.

2.2 Experimental Design

RSM was used for the experimental design of fibre enrichment in a cake matrix with the software Design Expert 9 (StatEase, Minneapolis, MN, USA). A five-factorial, face-centred, central composite design was chosen with single factorial points and four repetitions of the centre point. Different concentrations of SFC (low 0%, medium 0.25% and high 0.5%), Fibersym® RW (low 0%, medium 7.5% and high 15%), GENU® Pectin (low 0%, medium 4% and high 8%), PromOat® (low 0%, medium 6.25% and high 12.5%) and VITACEL L 600-30 (low 0%, medium 3.75% and high 7.5%) were used as variable parameters of the experiment. The maximum concentration of fibre ingredients was determined through preliminary trials based on a visual characterisation, ensuring that the DF inclusion did not compromise quality of the cake compare to the cake without fibre addition (data not shown). The preliminary test analysed key characteristics such as dome asymmetry, colour variation, and differences in internal structure were closely monitored during these evaluations. The medium concentration was defined as half of the maximum fibre concentration established for each ingredient. Finally, the low concentration was set as 0% for all the fibre ingredients to enable comparison with the control cake and to assess the individual impact of each fibre on the cake matrix. Table 1 outlines the different ingredient combinations used in cake formulations across 46 runs, with DF concentrations expressed based on BF substitution. The effects of both individual and combined fibre ingredients on cake characteristics were analysed by assessing predicted fibre concentration, bake loss, specific volume, slice area, cells count, holes count, cells area, cell diameter, hardness and resilience, as described in the following sections. To examine fibre-to-fibre interactions, multiple models were developed using linear and two-factor interaction approaches in Design Expert. The statistical significance of each model was assessed, along with the significance of individual variables and their interactions. A model was considered valid if it was statistically significant and exhibited an insignificant lack-of-fit (LOF), allowing for the determination of fibre inclusion levels that could coexist in the fibre-enriched cake system. Model refinement was carried out through backward elimination regression, discarding insignificant terms with an α threshold of 0.1. For models that met

significance criteria with an insignificant LOF, 3D response surface plots were generated.

Table 1. Experimental design for the investigation of fibre-to-fibre interactions in a cake system reporting formulations of BF plus fibre ingredients making up a total of 100 [%] by SFC, Fibersym® RW, GENU® Pectin, PromOat® and VITACEL L 600-30, and Viten®. Run 15 represents the BF control cake.

Run	BF [%]	SFC [%]	Fibersym® RW [%]	GENU® Pectin [%]	PromOat® [%]	VITACEL L 600-30 [%]	Viten® [%]
1	79	0.5	0	8	12.5	0	1.77
2	72.5	0	15	0	12.5	0	2.65
3	72	0.5	15	0	12.5	0	2.67
4	91.5	0.5	0	8	0	0	0.92
5	82	0.25	7.5	4	6.25	0	1.78
6	69	0.5	15	8	0	7.5	3.62
7	70.75	0.25	15	4	6.25	3.75	3.14
8	57	0	15	8	12.5	7.5	4.44
9	64.5	0	15	8	12.5	0	3.54
10	78.5	0	7.5	4	6.25	3.75	2.22
11	64.5	0.5	15	0	12.5	7.5	3.57
12	87.5	0	0	0	12.5	0	0.85
13	78.25	0.25	7.5	4	6.25	3.75	2.23
14	79.5	0	0	8	12.5	0	1.74
15	100	0	0	0	0	0	0
16	84	0.5	0	8	0	7.5	1.82
17	92	0	0	8	0	0	0.90
18	82.25	0.25	7.5	0	6.25	3.75	1.79
19	85	0	15	0	0	0	1.80
20	99.5	0.5	0	0	0	0	0.02
21	92	0.5	0	0	0	7.5	0.92
22	78.25	0.25	7.5	4	6.25	3.75	2.23
23	76.5	0.5	15	8	0	0	2.72
24	77	0	15	8	0	0	2.70
25	87	0.5	0	0	12.5	0	0.87
26	78.25	0.25	7.5	4	6.25	3.75	2.23
27	77	0.5	15	0	0	7.5	2.73
28	84.5	0.25	7.5	4	0	3.75	1.81
29	78	0.5	7.5	4	6.25	3.75	2.25
30	69.5	0	15	8	0	7.5	3.60
31	77.5	0	15	0	0	7.5	2.70
32	64	0.5	15	8	12.5	0	3.57
33	85.75	0.25	0	4	6.25	3.75	1.33
34	72	0	0	8	12.5	7.5	2.64
35	84.5	0	0	8	0	7.5	1.80
36	79.5	0.5	0	0	12.5	7.5	1.77
37	74.25	0.25	7.5	8	6.25	3.75	2.68
38	72	0.25	7.5	4	12.5	3.75	2.66
39	84.5	0.5	15	0	0	0	1.83
40	92.5	0	0	0	0	7.5	0.90
41	80	0	0	0	12.5	7.5	1.75
42	56.5	0.5	15	8	12.5	7.5	4.47
43	65	0	15	0	12.5	7.5	3.55
44	78.25	0.25	7.5	4	6.25	3.75	2.23
45	71.5	0.5	0	8	12.5	7.5	2.67
46	74.5	0.25	7.5	4	6.25	7.5	2.68

2.3 Batter and Cake Preparation

The control recipe was composed of 100% BF, 80% butter, 0.45% salt, 100% sugar, 3.64% baking powder and 109% eggs (percentages expressed based on 100% BF). The batters were prepared using a Kenwood Chef XL Titanium KVL8300S stand mixer with a whisk attachment (Kenwood, Havant, UK). First, the eggs and sugar were mixed at speed 4 for 2 min to form a premix. Next, the dry ingredients were added and mixed at the same speed for another 2 min. The melted butter was then incorporated, followed by a final mixing step at speed 1 for 1 min. The butter was melted in a microwave (Caterlite, Bristol, UK) using the defrost setting for 2 min and added to the dry ingredients, followed by a final mixing step at

speed 1 for 1 min. Each batch of cake batter (250 g) was weighed and poured into 2 different mini pans (5.81 cm height, top and bottom lengths 14.96 cm and 13.85 cm, and top and bottom widths 8.52 cm and 7.52 cm). Baking was carried out in a preheated, top/bottom-heated, unventilated deck oven (MIWE condo, Arnstein, Germany) at 180 °C for 36 min. After baking, the cakes were cooled in the tin for 1 h before being removed and allowed to cool further in open air for another hour prior to analysis. The same procedure was followed for the fibre-enriched runs, in which a blend of BF, vital gluten and fibre ingredients prepared according to the experimental design shown in Table 1 was added to the remaining ingredients previously listed. Formulations displayed in Table 1 were baked once, yielding two cakes per formulation. For analyses involving individual slices, the cakes were cut into 25 mm thick slices, excluding the end slices from analysis, resulting in four slices per cake.

2.4 Impact of Different Fibre Combination on Cake Quality

2.4.1 Bake loss

The bake loss (%), representing the moisture lost during the baking process, of two cakes per batch was obtained weighing the cakes before and after baking.

2.4.2 Specific Volume

The specific volume (mL/ g) of two cakes per batch was investigated with the Volscan Profiler (Stable Micro Systems, Surrey, UK).

2.4.3 Crumb Structure

The crumb structure, including slice area, number of cells, number of holes, area of cells and cell diameter, was investigated for 8 slices of cake per batch using the C-Cell Imaging System (Calibre Control International Ltd., Warrington, UK).

2.4.4 Crumb Texture

The crumb texture, including hardness and resilience, was determined for 8 slices of cake per batch using texture profile analysis (TPA) with the TA-XT2i texture analyser (Stable Micro Systems, Godalming, UK), attached with a flat-ended cylindrical aluminium probe (diameter: 25 mm) and a TA-90 platform. The test was performed as described by Halm et al. (2024).

2.5 Combination of Fibre Ingredients

The most suitable fibre blend and inclusion level that minimally affected cake quality were identified using the Design Expert v.9 simulation software. The objective was to replicate the quality of the control cake (CC) observed in run 15 while incorporating the highest possible amount of DF. To achieve this, maximising specific volume and fibre content while minimising crumb hardness and number of holes

were selected as the most important/desirable parameters for the optimised formulation. Furthermore, based on overall performance across the various analyses, the inclusion of PromOat® and GENU® Pectin was maximised. As a result of the RSM optimisation tool, 38.45% of flour was replaced with 0.49% SFC , 14.99 Fibersym® RW , 7.99% GENU® Pectin , 7.49% PromOat® and 7.49% VITACEL L 600-30 , resulting in the fibre-enriched cake (FeC) formulation. In addition to the cake analyses previously discussed, the following batter analyses, additional cake analyses, *in vitro* starch digestion and sensory analyses were performed on CC and FeC. Both recipes were produced in triplicate, resulting in two cakes or 8 slices per batch.

2.5.1 Batter Viscoelastic Properties

The viscoelastic properties of CC and FeC batters were studied using a Rheometer Physica MCR 301 (Anton Parr GmbH, Ostfildern, Germany). The cake batter was transferred into a concentric cylinder measurement system and filled to the level mark, and a compatible probe (26.7 mm diameter) was used. The apparent viscosity (Pa·s) was measured at a shear rate of 10 s^{-1} and a temperature of 20 °C. The analyses was performed in duplicate per batch.

2.5.2 Batter Performance during Baking

The batter performance, specifically changes in the viscoelastic properties of CC and FeC during heating, was assessed using the micro-baking test described by Schirmer et al. (2012). A Rheometer Physica MCR 301 (Anton Paar GmbH, Ostfildern, Germany) was used for the analysis. The cake batter was placed on a heated parallel plate equipped with a plate–plate measurement system (50 mm diameter). The complex modulus (G^*) and the temperature (T_i) at the inflection point of the curve were recorded. The analyses were performed in duplicate per batch.

2.5.3 Cake Microstructure

The cake microstructure was visualised using a JEOL Scanning Electron Microscope (JSM-5510, Jeol Ltd., Tokyo, Japan). Sample preparation and analyses were performed as reported by Atzler et al. (2024).

2.5.4 Cake Compositional Analyses

Compositional analyses of CC and FeC were completed externally by the accredited laboratory Chelab S.R.L., Resana, Italy. The following parameters were assessed using the laboratory internal methods: energy content, moisture, total fats, carbohydrates, sugars, proteins, ash and fibre. Moisture was calculated using a method which was developed based on AOAC 950.46 and AOAC 952.08 (AOAC International, 1991a, 1961). The fat concentration was determined by a method reported as MP 2598 rev 0 2022. For total protein quantification, a method based on AOAC 990.03, AOAC 992.15, and AOAC 992.23 was used (AOAC International, 2002, 2000b,c). Ash quantities were assessed by a method developed based

on AOAC 945.46, AOAC 923.03, AOAC 938.08, and AOAC 920.93 (AOAC International, 2000a, 1990b, 2005, 1990a). The concentration of carbohydrates and energy value was calculated by a method developed based on AOAC 986.25 (AOAC International, 1991b).

The fibre concentration were analysed with two different methods, AOAC 991.43 and AOAC 2017.16 (AOAC International, 1991c, 2017). The former quantifies high molecular weight dietary fibre (HMWDF), while the latter measures HMWDF and low molecular weight soluble dietary fibre that precipitates in ethanol (SDFS).

2.5.5 Staling Rate

To evaluate the change in texture over time, staling was assessed by measuring crumb hardness using the Texture Profile Analyzer, as described earlier. One cake per batch was analysed five days after production, following storage in a sealed plastic bag. The following equation was applied (1):

$$Staling\ Rate = \frac{Crumb\ Hardness\ at\ 120\ \text{h}\ [\text{N}] - Crumb\ Hardness\ at\ 2\ \text{h}\ [\text{N}]}{Crumb\ Hardness\ at\ 2\ \text{h}\ [\text{N}]} \quad (1)$$

2.5.6 Water activity

Water activity (a_w) was measured using an AquaLab Series 3 (Decagon Devices Inc., Pullman, WA, USA). For each cake, 2 g of crumb was placed in a sealed container and allowed to equilibrate for 5 min before conducting the test.

2.5.7 Microbial shelf life

To evaluate the shelf life of the cake, the microbial growth was monitored over 23 days using a mould environmental challenge method reported by Dal Bello et al. (2007). In summary, 8 centre slices were placed on a sterile metal rack, exposing both sides to the environment for 5 min. Each slice was then sealed in a sterile bag, with a filter pipette tip inserted to maintain constant aerobic conditions. The samples were stored in a temperature and humidity controlled chamber (KOMA SunRiser, Roermond, The Netherlands) at 20 $\pm$ 1 °C and 50% RH. Over the period of 23 days, the slices were assessed daily for mould growth. Visual evaluation categorised mould progression into five stages: “mould free”, “mould growth $<$10%”, “10–24% mould growth”, “25–49% mould growth” and “mould growth $>$50%”.

2.5.8 Release of Reducing Sugars during in-vitro Starch Digestion

An *in vitro* starch digestion assay, specifically designed for fibre-enriched products, was conducted following the methodology described by Brennan and Tudorica (2008). This assay involved the enzymatic breakdown of starch into reducing sugars over a defined period. To quantify the concentration of reducing sugars (maltose) released over time, 100 μL of each sample was mixed with 100 μL of a 40 mM 3,5-dinitrosalicylic acid solution, heated at 100 °C for 15 n, and subsequently diluted with 1 mL of deionised

water. Each sample was analysed in duplicate. Starch digestibility, expressed as Reducing Sugar Release (RSR) (%) over time, was calculated using the following equation 2:

$$RSR\% = \frac{A_{sample} \times 500 \times 0.95}{A_{maltose} \times available\ carbohydrate} \times 100 \quad (2)$$

The absorbance of the active sample at 546 nm is denoted as Asample. The total volume of the solution is 500 mL, and a conversion factor of 0.95 is applied to convert maltose measurements to starch content. Amaltose refers to the absorbance corresponding to 1 mg of pure maltose dissolved in 1 mL of buffer solution. The available carbohydrate — encompassing both sugar and digestible starch from 4 g of the sample — is measured in milligrams and was determined using the Megazyme kit K-RAPRS (Bray, Ireland).

2.5.9 Sensory evaluation

The sensory properties of the cake were investigated by performing a descriptive analysis test using a semi-experienced sensory panel (n = 12, age range 23–45) from Food Science department of the University College Cork. Panelists evaluated the intensity of the hedonic attributes ”appearance”, ”aroma”, ”taste”, ”flavour”, ”texture”, ”overall”, flavour attributes ”intensity”, ”caramel”, ”bran/cereal”, ”butter”, ”egg” and taste attributes ”intensity”, ”sweetness”, ”saltiness” and ”aftertaste” on a scale from 0, ”not present” to 10, ”extremely present”. All participants were provided with written information about the study and gave their informed consent to participate. Each panellist received a 10 g portion of each cake sample, presented individually on a white plastic plate labelled with a three-digit random code. Samples were evaluated in duplicate within individual, air-conditioned sensory booths maintained at 22 °C. Room-temperature water was provided for palate cleansing. All cake samples were assessed on the same day as they were baked.

2.6 Statistical Analyses

All measurements were performed in triplicate unless otherwise stated. The statistical analyses of the dataset related to the RSM were conducted using the Design Expert software, as detailed in Section 2.2. Statistical analyses of the final products were carried out with GraphPad Prism version 10 (GRAPH PAD Software Inc., Solana Beach, CA, USA); the significance level was set at $\alpha \lesssim 0.05$. A t-test was used to assess and identify statistically significant differences among CC and FeC.

3 RESULTS

3.1 Influence of fibre ingredients and fibre-fibre interaction in cake matrix

The impact of the fortification of cake with soluble (SFC, GENU® Pectin and PromOat®) and insoluble (Fibersym® RW and VITACEL L 600-30) fibre ingredients was studied. RSM was used to investigate the impact of single fibre ingredients (run 12, run 17, run 19, run 20, and run 40) and their combinations at different concentrations. The images of the various cake formulations are shown in Figure 1 and the results are displayed in Table 2.

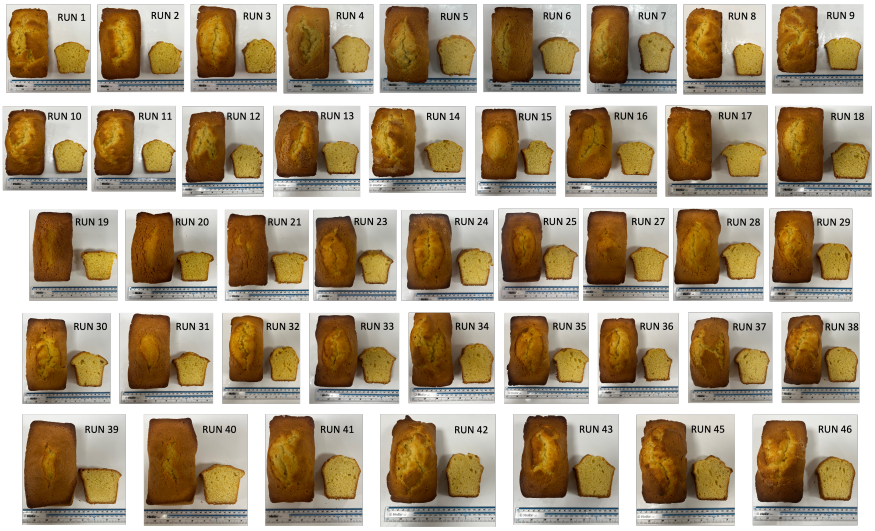


Figure 1. Appearance of the different cake formulations.

The predicted fibre concentration of the products was estimated based on the fibre content of the individual ingredients. The control formulation (run 15) contained 1.73 g of fibre per 100 g, while the fibre-enriched formulations exhibited values ranging from 1.81 to 7.36 g per 100 g.

The amount of water lost during the baking process is referred to as bake loss. The control formulation (run 15) showed a bake loss of 9.51 $\pm$ 0.24%. Only two formulations resulted in a higher bake loss compared to run 15; run 20 which had the maximum concentration of SFC , and run 39 which combined 0.5% SFC and 15% Fibersym® RW (10.51 $\pm$ 0.32% and 9.80 $\pm$ 0.05%, respectively). The other fibre-containing formulations showed a bake loss ranging between 7.28 $\pm$ 0.21 and 9.47 $\pm$ 0.11%.

The specific volume is a crucial indicator of cake quality, reflecting its ability to rise during baking. The control formulation (run 15) had a specific volume of 2.20 $\pm$ 0.01 mL/g, whereas the fibre-containing formulations ranged between 1.96 $\pm$ 0.06 and 2.61 $\pm$ 0.03 mL/g. When the fibre ingredients were added singly, the specific volume increased, except in the case of PromOat® inclusion (2.13 $\pm$ 0.02 mL/g). This ingredient combined with GENU® Pectin (runs 1 and 14) resulted in a decrease in the specific volume (1.98 $\pm$ 0.04 and 2.02 $\pm$ 0.02 mL/g), with a similar trend observed when it was combined with Fibersym®

Table 2. Characteristics of cakes fortified with different amounts and combinations of SFC, Fibersym® RW, GENU® Pectin, PromOat®, VITACEL L 600-30, and Viten® (specific formulation of each run reported in Table 1).

Run	Predicted Fibre Concentration [g/100 g]	Bake Loss [%]	Specific Volume [mL/g]	Slice Area [mm^2]	Number of Cells	Number of Holes	Area of Cells [%]	Cell Diameter [mm]	Crumb Hardness [N]	Crumb Resilience [–]
1	3.75	7.39 ± 0.29	1.98 ± 0.04	4173 ± 167	2473 ± 180	1.36 ± 1.33	50.71 ± 0.49	2.40 ± 0.11	5.02 ± 0.73	0.19 ± 0.03
2	4.55	7.57 ± 0.42	1.96 ± 0.02	4220 ± 180	2366 ± 128	0.59 ± 0.59	51.75 ± 0.66	2.53 ± 0.19	6.60 ± 0.27	0.22 ± 0.02
3	4.61	7.77 ± 0.21	2.07 ± 0.04	4421 ± 183	2566 ± 166	0.93 ± 0.73	52.16 ± 0.82	2.61 ± 0.26	5.10 ± 0.62	0.21 ± 0.02
4	2.62	8.19 ± 0.24	2.16 ± 0.01	4491 ± 208	2552 ± 202	1.42 ± 0.89	51.68 ± 1.15	2.45 ± 0.28	4.65 ± 0.25	0.20 ± 0.02
5	3.58	7.66 ± 0.05	2.23 ± 0.03	4696 ± 255	2662 ± 285	1.60 ± 1.02	52.14 ± 1.10	2.51 ± 0.35	4.50 ± 0.73	0.21 ± 0.02
6	6.20	8.42 ± 0.09	2.38 ± 0.03	4729 ± 201	2503 ± 184	1.36 ± 0.71	52.62 ± 1.52	2.68 ± 0.29	4.43 ± 0.34	0.17 ± 0.01
7	5.42	8.86 ± 0.54	2.33 ± 0.13	4651 ± 225	2545 ± 147	1.30 ± 0.96	52.99 ± 0.94	2.66 ± 0.24	4.02 ± 0.37	0.22 ± 0.02
8	7.27	8.16 ± 0.39	1.97 ± 0.03	4090 ± 118	2248 ± 103	1.09 ± 0.54	52.07 ± 0.84	2.64 ± 0.27	6.09 ± 0.54	0.18 ± 0.02
9	5.41	7.99 ± 0.01	1.96 ± 0.06	4101 ± 152	2227 ± 152	1.03 ± 1.00	52.36 ± 1.00	2.73 ± 0.33	4.85 ± 0.27	0.18 ± 0.01
10	4.54	8.88 ± 0.07	2.25 ± 0.03	4686 ± 294	2377 ± 157	0.91 ± 0.64	53.74 ± 1.09	3.10 ± 0.34	5.15 ± 0.37	0.21 ± 0.02
11	6.51	8.55 ± 0.63	2.22 ± 0.03	4572 ± 204	2422 ± 149	0.70 ± 0.71	53.36 ± 0.80	2.89 ± 0.25	4.99 ± 0.53	0.21 ± 0.02
12	2.87	8.07 ± 0.13	2.13 ± 0.02	4407 ± 241	2195 ± 227	0.51 ± 0.63	54.15 ± 1.52	3.33 ± 0.52	6.57 ± 0.49	0.22 ± 0.01
13	4.56	8.86 ± 0.31	2.31 ± 0.00	4694 ± 261	2418 ± 206	1.48 ± 1.00	53.18 ± 0.93	2.73 ± 0.30	4.94 ± 0.62	0.17 ± 0.01
14	3.69	7.43 ± 0.03	2.02 ± 0.02	4323 ± 208	2352 ± 127	0.62 ± 0.70	51.48 ± 0.51	2.70 ± 0.23	5.83 ± 0.53	0.19 ± 0.01
15	1.73	9.51 ± 0.24	2.20 ± 0.01	4515 ± 406	2193 ± 247	0.25 ± 0.46	53.98 ± 1.20	3.45 ± 0.54	6.36 ± 0.34	0.24 ± 0.01
16	4.47	7.90 ± 0.26	2.33 ± 0.03	4582 ± 361	2233 ± 151	0.61 ± 0.52	53.17 ± 1.75	3.19 ± 0.53	3.80 ± 0.40	0.21 ± 0.02
17	2.59	8.98 ± 0.19	2.31 ± 0.16	4593 ± 399	2672 ± 326	1.56 ± 0.66	51.55 ± 1.71	2.40 ± 0.33	4.51 ± 0.60	0.17 ± 0.02
18	4.13	8.77 ± 0.44	2.11 ± 0.02	4298 ± 345	2365 ± 197	0.72 ± 0.54	52.68 ± 1.35	2.62 ± 0.34	6.79 ± 0.70	0.17 ± 0.01
19	3.45	8.96 ± 0.43	2.36 ± 0.11	4603 ± 234	2089 ± 184	0.00 ± 0.00	55.68 ± 1.04	4.65 ± 0.59	3.47 ± 0.49	0.26 ± 0.01
20	1.81	10.51 ± 0.32	2.30 ± 0.00	4391 ± 197	2102 ± 168	0.11 ± 0.32	54.29 ± 1.05	3.54 ± 0.53	4.09 ± 0.44	0.19 ± 0.01
21	3.65	8.66 ± 0.10	2.31 ± 0.08	4490 ± 176	2081 ± 162	0.00 ± 0.00	54.60 ± 1.01	3.76 ± 0.66	4.26 ± 0.56	0.18 ± 0.01
22	4.35	8.14 ± 0.64	2.02 ± 0.04	4483 ± 309	3050 ± 323	3.19 ± 1.06	51.25 ± 1.21	1.98 ± 0.22	5.31 ± 0.46	0.24 ± 0.01
23	4.31	8.56 ± 0.27	2.61 ± 0.03	5179 ± 464	2874 ± 295	2.12 ± 0.80	53.31 ± 1.35	2.47 ± 0.21	3.71 ± 0.35	0.25 ± 0.02
24	2.94	8.97 ± 0.09	2.61 ± 0.03	5244 ± 427	2893 ± 336	1.57 ± 1.01	53.52 ± 1.80	2.61 ± 0.48	4.04 ± 0.37	0.28 ± 0.01
25	2.94	8.67 ± 0.33	2.25 ± 0.02	4742 ± 386	2611 ± 314	0.94 ± 0.48	53.42 ± 1.91	2.81 ± 0.57	4.92 ± 0.19	0.26 ± 0.02
26	4.50	7.49 ± 0.25	1.99 ± 0.07	4401 ± 329	2993 ± 360	2.91 ± 0.79	50.82 ± 1.54	1.99 ± 0.22	5.90 ± 0.61	0.26 ± 0.02
27	5.38	8.99 ± 0.74	2.43 ± 0.10	4768 ± 423	2556 ± 271	0.50 ± 0.76	52.70 ± 1.54	2.65 ± 0.43	5.92 ± 1.11	0.15 ± 0.01
28	4.01	9.47 ± 0.11	2.59 ± 0.08	5107 ± 393	2912 ± 228	1.65 ± 0.58	52.12 ± 1.30	2.43 ± 0.30	5.24 ± 0.85	0.22 ± 0.06
29	4.58	8.59 ± 0.01	2.33 ± 0.07	4779 ± 421	2772 ± 344	1.28 ± 0.88	52.13 ± 1.71	2.39 ± 0.31	6.32 ± 1.09	0.21 ± 0.02
30	6.11	7.89 ± 0.20	2.61 ± 0.04	5184 ± 379	2755 ± 281	1.47 ± 1.17	53.14 ± 1.87	2.71 ± 0.43	4.45 ± 0.41	0.22 ± 0.06
31	5.29	8.38 ± 0.09	2.39 ± 0.01	4750 ± 348	2361 ± 336	0.29 ± 0.45	53.97 ± 1.64	3.08 ± 0.57	5.91 ± 0.51	0.20 ± 0.03
32	5.46	7.83 ± 0.01	2.09 ± 0.01	4424 ± 264	2921 ± 191	3.15 ± 0.80	50.28 ± 1.05	2.05 ± 0.09	6.57 ± 0.59	0.25 ± 0.17
33	3.69	8.57 ± 0.48	2.44 ± 0.04	5061 ± 422	2736 ± 243	0.97 ± 0.65	53.41 ± 1.48	2.69 ± 0.21	5.97 ± 0.61	0.22 ± 0.01
34	5.56	7.82 ± 0.02	2.16 ± 0.03	4498 ± 279	2644 ± 196	1.67 ± 1.30	51.79 ± 1.36	2.42 ± 0.24	7.28 ± 0.46	0.21 ± 0.02
35	4.49	9.32 ± 0.38	2.53 ± 0.02	5123 ± 405	2869 ± 261	1.46 ± 1.25	52.63 ± 1.08	2.54 ± 0.23	4.68 ± 0.48	0.27 ± 0.11
36	4.74	7.31 ± 0.06	2.21 ± 0.10	4674 ± 437	2406 ± 175	0.44 ± 0.61	53.84 ± 1.23	3.14 ± 0.48	5.82 ± 0.92	0.24 ± 0.02
37	5.01	9.14 ± 0.32	2.51 ± 0.10	5086 ± 386	3057 ± 239	2.00 ± 1.10	51.54 ± 1.35	2.24 ± 0.21	5.36 ± 0.79	0.24 ± 0.18
38	5.16	9.11 ± 0.06	2.36 ± 0.03	4829 ± 423	2951 ± 294	2.02 ± 0.85	51.75 ± 1.62	2.21 ± 0.20	6.68 ± 0.43	0.19 ± 0.02
39	3.54	9.80 ± 0.05	2.53 ± 0.01	4689 ± 183	2490 ± 208	0.61 ± 0.67	52.77 ± 1.17	2.66 ± 0.33	5.50 ± 0.80	0.17 ± 0.03
40	3.61	8.99 ± 0.22	2.37 ± 0.07	4631 ± 279	2490 ± 309	0.62 ± 0.46	52.80 ± 1.19	2.69 ± 0.39	6.16 ± 0.90	0.17 ± 0.01
41	4.69	7.28 ± 0.21	2.38 ± 0.02	4953 ± 392	2743 ± 227	1.25 ± 0.67	52.78 ± 0.82	2.59 ± 0.23	5.94 ± 0.67	0.23 ± 0.06
42	7.36	8.70 ± 0.02	2.35 ± 0.05	4798 ± 277	3025 ± 285	2.30 ± 0.57	50.90 ± 1.38	2.14 ± 0.27	7.05 ± 0.93	0.23 ± 0.19
43	6.49	9.06 ± 0.24	2.26 ± 0.04	4593 ± 352	2720 ± 223	0.99 ± 0.71	51.74 ± 1.19	2.29 ± 0.27	8.58 ± 1.15	0.20 ± 0.02
44	4.51	7.69 ± 0.54	1.99 ± 0.02	4406 ± 287	2665 ± 398	2.24 ± 0.82	50.53 ± 1.27	2.00 ± 0.23	6.54 ± 1.14	0.24 ± 0.02
45	5.67	8.76 ± 0.19	2.31 ± 0.00	4715 ± 241	2706 ± 168	1.70 ± 0.71	52.31 ± 1.57	2.41 ± 0.22	6.07 ± 0.65	0.23 ± 0.12
46	5.51	9.07 ± 0.06	2.54 ± 0.03	5160 ± 374	2804 ± 234	0.79 ± 0.64	53.26 ± 1.91	2.72 ± 0.44	5.34 ± 0.42	0.24 ± 0.05

RW (run 2, specific volume of 1.96 ± 0.06 mL/g). The formulation containing the combination of insoluble fibres (Fibersym® RW and VITACEL L 600-30 , run 31) resulted in a higher specific volume (2.39 ± 0.01 mL/g) than run 15. In general, when the fibre ingredients were combined as their maximum concentrations, a higher specific volume was reported.

Slice area (mm^2), number of cells, number of holes and cell diameter (mm) were investigated to analyse the structure of the crumb. The formulation without fibre addition (run 15) showed a slice area of 4515 ± 406 mm^2, while the slice area of the fibre-containing formulations ranged between 4101 ± 152 and 5244 ± 427 mm^2. These results are in line with what was observed in the specific volume. The number of cells in the fibre-containing formulations ranging between 2081 ± 162 and 3057 ± 239. Run 15, without the fibre inclusion, showed a cell number of 2193 ± 247. Among individual fibre inclusions and compared to the run 15, PromOat® , GENU® Pectin , and VITACEL L 600-30 (Runs 12, 17, and 40, respectively) increased the number of cells, while SFC and Fibersym® RW (Runs 20 and 19, respectively) led to a decrease in this value. In general, the number of cells always increased in the runs

with combinations of soluble fibres (SFC, GENU® pectin and PromOat® Beta Glucan runs 1, 4, 14 and 25), insoluble fibres (Fibersymym® RW and VITACEL L 600-30 , run 31) and soluble-insoluble fibres (SFC, GENU® pectin, PromOat® Beta Glucan, Fibersymym® RW and VITACEL L 600-30 runs 13, 22, 26 42 and 44). An inverse relationship was observed between the number of cells and their diameter, whereby an increase in cell number corresponded to a decrease in diameter, and vice versa. The number of holes in the control cake (run 15) was 0.25 ± 0.46. Generally, fibre inclusion increased the number of holes in the slices of cake (values between 0.29 ± 0.45 and 3.19 ± 1.06), except for runs 19, 20 and 21.

Hardness and resilience which are key textural properties that influence overall cake quality were investigated. The control (run 15) had a hardness of 6.36 ± 0.34 N and a resilience of 0.24 ± 0.01. The singular inclusion of SFC (run 20), GENU® Pectin (run 17), Fibersym® RW (run 19) and VITACEL L 600-30 (run 40) decreased the hardness (4.51 ± 0.60 N, 3.47 ± 0.49 N, 4.09 ± 0.44 N and 6.16 ± 0.90 N, respectively). In contrast, the inclusion of PromOat® decreased it (6.57 ± 0.49 N). In general, the hardness decreased in the soluble-soluble (runs 1, 4, 14 and 25), insoluble-insoluble (run 31) but increased in run 2 which contained maximum concentration of the fibre mixture (run 42 7.05 ± 0.93 N). The fibre inclusion resulted in similar trends in resilience.

3.2 Combination of fibre ingredients in batter and cake matrix

To identify the final combination and concentration of DF ingredients that can be incorporated into the cake system with minimal impact on its properties, the proposed linear and two-factorial interaction models in Design Expert must be statistically significant and exhibit an insignificant lack of fit (LOF). The impact of fibre-fibre interactions in different runs was evaluated for each response. The inclusion of all fibre types resulted in an increase in specific volume, except for combination of PromOat® with GENU® Pectin or Fibersym® RW . Additionally, hardness decreased with the addition of SFC , Fibersym® RW , and GENU® Pectin ; while the inclusion of PromOat® and VITACEL L 600-30 led to hardness values that were not significantly different from the control. All the responses demonstrated a acceptable fit to the predicted model, showing statistical significance and an insignificant lack of fit. Based on the data collected and the statistical evaluations, the Design Expert tool determined an improved fibre-enriched cake formulation (FeC), in which 38.45% of flour was replaced with 0.49% SFC , 14.99% Fibersym® RW , 7.99% GENU® Pectin , 7.49% PromOat® , 7.49% VITACEL L 600-30 and 4.13% Viten®. The bake loss (8.36%), specific volume (2.37 mL/g), crumb hardness (5.38 N), number of holes (1.49) and predicted fibre (6.89 g/100 g) were theoretically estimated by the RSM. Finally, the two final formulations (CC and FeC) underwent all the analyses conducted for the RSM runs, along with the additional tests outlined in Paragraph 2.5.

3.2.1 Batter analysis

The results of the cake batter analysis are displayed in Table 4.

The T_i at which the cake batter transitions from a liquid to a solid state was identified using the inflection point of G* (Figure 2). This value provides key insights into structural transition of the batter, the processes of starch gelatinisation and protein coagulation. The T_i of the CC batter was 75 $\pm$ 0.00 °C, which did not significantly differs from that of the FeC batter (79 $\pm$ 0.00 °C).

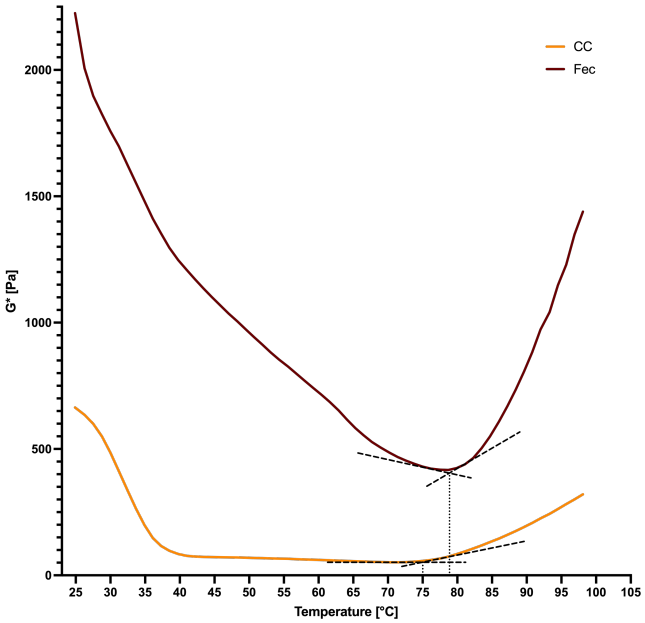


Figure 2. Microbaking curve profiles of CC and FeC. The graph illustrates the change in batter microstructure, from a more viscous to a more elastic state, through the evolution of complex modulus (G*) [Pa] in relation to temperature [°C].

The CC batter exhibited an average apparent viscosity of 18.85 $\pm$ 3.16 Pa·s, whereas the FeC batter was significantly more viscous, measuring 92.20 $\pm$ 7.88 Pa·s.

3.2.2 Cake analysis

A visual representation of the CC and FeC is shown in Figure 3, along with the cake microstructure which was investigated using scanning electron microscopy. The CC exhibits a homogeneous distribution of swollen starch granules embedded within the gluten network, which appears as an intertwined matrix. In contrast, the FeP presents a film-like structure with an almost complete absence of visible starch granules. Additionally, the structure appears to be more dense compared to CC.

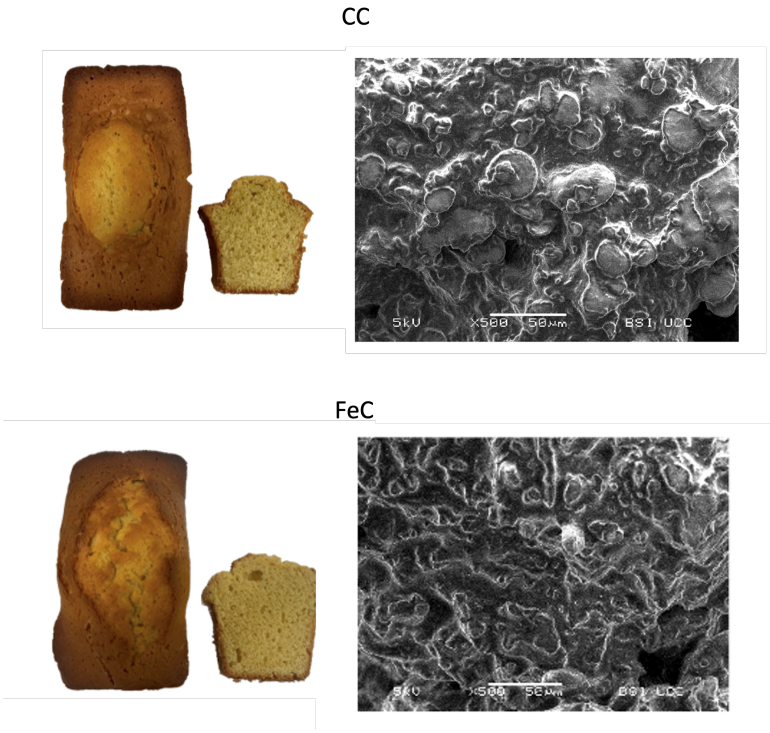


Figure 3. Images of CC (top) and FeC (bottom). Left pictures represent the cakes cooked with standard procedure. Right pictures are SEM micrographs of freeze-dried cake crumb at 500 x magnification.

Table 3. Composition of the CC and FeC, expressed as g/100 g. The values are presented as mean ± standard deviation.

	CC	**FeC**
Energy [kcal/100 g]	426 ± 8	413 ± 7
Moisture	19.91 ± 0.61	21.03 ± 0.63
Total fats	22.1 ± 1.4	20.3 ± 1.3
Carbohydrates	50.76 ± 1.59	51.33 ± 1.51
Proteins (N x 6.25)	6.06 ± 0.42	6.13 ± 0.43
Ash	1.17 ± 0.08	1.21 ± 0.09
AOAC 991.43		
Total dietary fibre (HMWDF)	0.80 ± 0.13	8.10 ± 1.3
AOAC 2017.16		
Total dietary fibre	1.73 ± 0.30	5.05 ± 1.11
• *HMWDF (IDF & SDFP)*	1.1 ± 0.26	4.5 ± 1.1
• *SDFS*	0.63 ± 0.15	0.55 ± 0.13

HMWDF, high molecular weight dietary fibre; IDF, insoluble dietary fibre; SDFP, high-molecular-weight soluble dietary fibre; SDFS, low-molecular-weight soluble dietary fibre

The nutritional analysis (Table 3) revealed in FeC a decrease in energy value (413 ± 7 kcal/100 g) compared to CC, 426 ± 8 kcal/100 g. Dietary fibre quantification using AOAC 991.43 and 2017.16 methods both demonstrated elevated HMWDF levels in the FeC (AOAC 991.43: 8.10 ± 1.3 g/100 g; AOAC 2017.16: 4.5 ± 1.1 g/100 g) relative to the CC (0.80 ± 0.13 g/100 g and 1.1 ± 0.26 g/100 g, respectively). Notably, the remaining nutritional components (e.g., moisture, fat, protein and ashes)

appeared to be comparable.

The results of the cake analysis are displayed in Table 4.

The bake loss, volume and slice area showed no significant differences between CC and FeC (9.11 $\pm$ 0.11% vs. 8.51 $\pm$ 0.79%, 2.43 $\pm$ 0.18 mL/g vs. 2.39 $\pm$ 0.06 mL/g and 4808 $\pm$ 420 mm^2 vs. 4917 $\pm$ 311 mm^2, respectively). Conversely, the two samples exhibited significant differences, with a higher number of cells and holes (2207 $\pm$ 243 vs. 2741 $\pm$ 249 and 0.17 $\pm$ 0.38 vs. 1.55 $\pm$ 0.96, respectively), while cell area and diameter decreased (54.97 $\pm$ 1.42% vs. 52.39 $\pm$ 1.45% and 3.81 $\pm$ 0.70 mm vs. 2.58 $\pm$ 0.28 mm, respectively). Additionally, fibre inclusion did not significantly increase hardness or staling rate in FeC (5.60 $\pm$ 0.70 N and 1.06 $\pm$ 0.44) compared to CC (5.20 $\pm$ 0.97 N and 0.74 $\pm$ 0.22). Although, resilience decreases significantly by 17.39% in FeC. Finally, no significant differences were found in the water activity between the two samples.

Table 4. Cake characteristics of CC and FeC. The data are presented as mean $\pm$ standard deviation. Values in the same column followed by different letters are significantly different ($p < 0.05$).

Sample	Viscosity [Pa·s]	Bake Loss [%]	Specific Volume [mL/g]	Slice Area [mm^2]	Number of Cells	Number of Holes	Area of Cells [%]	Cell Diameter [mm]	Crumb Hardness [N]	Crumb Resilience	Stale Rate	a_w
CC	18.85 ± 3.16^a	9.11 ± 0.60^a	2.43 ± 0.18^a	4808 ± 420^a	2207 ± 243^a	0.17 ± 0.38^a	54.97 ± 1.42^a	3.81 ± 0.70^a	$5.20 \pm 0.97a^a$	0.23 ± 0.01^a	0.74 ± 0.22^a	0.89 ± 0.02^a
FeC	92.20 ± 7.88^b	8.51 ± 0.79^a	2.39 ± 0.06^a	4917 ± 311^a	2741 ± 249^b	1.55 ± 0.96^b	52.39 ± 1.45^b	2.58 ± 0.28^b	5.60 ± 0.70^a	0.19 ± 0.03^b	1.06 ± 0.44^a	0.88 ± 0.01^a

3.3 Impact of fibre mixture on shelf-life

The results of the microbial shelf-life analysis are presented in Figure 4. Mould growth was first observed on the CC after 9 days, whereas the FeC remained mould-free until day 22.

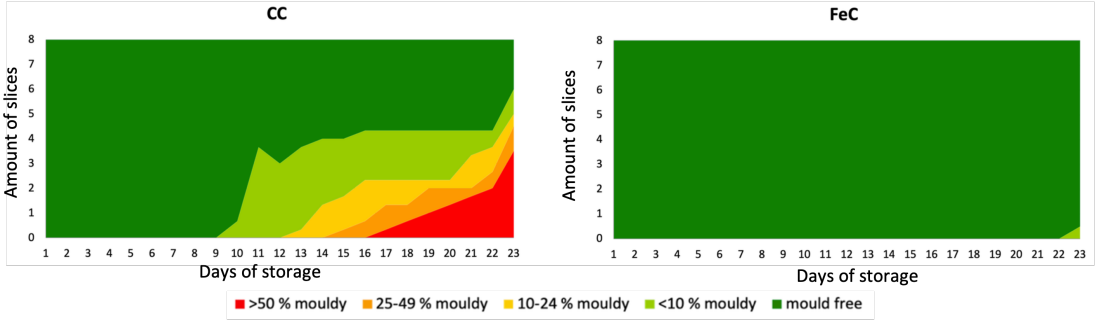


Figure 4. Microbial shelf-life evaluation of CC and FeC over 23 days.

3.4 Impact of fibre mixture on starch digestibility

Starch digestibility was analysed to gain insights into the cake's nutritional properties. The time-dependent release of reducing sugars (RSR) is presented in Figure 5. The inclusion of fibre decreased the rate at which reducing sugars were released over time in the FeC (0.11%/min), compared to the CC, which showed a faster release rate (0.14 %/min).

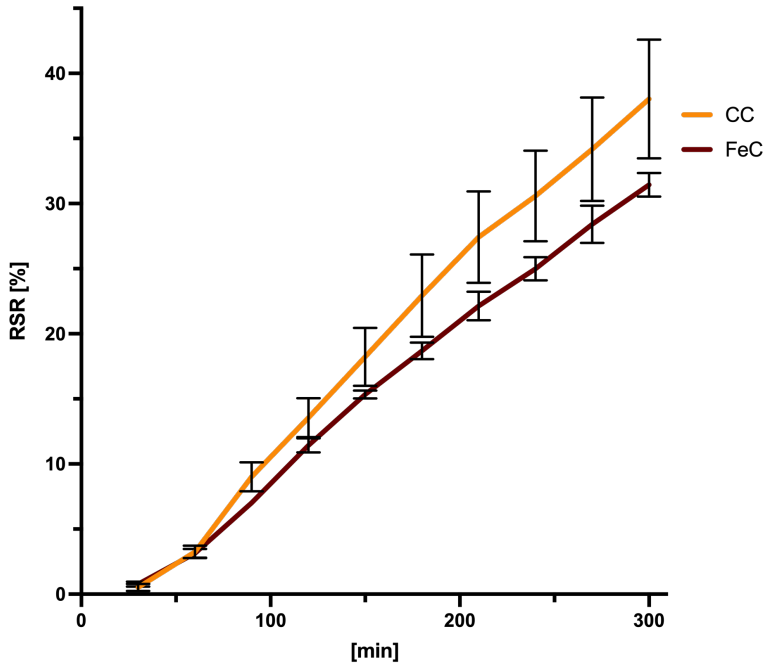


Figure 5. Release of reducing sugars (RSR) during in-vitro starch hydrolysis/digestion of CC and FeC samples over 300 min. The data are presented as mean ± standard deviation.

3.5 Sensory analysis

A sensory analysis was performed to evaluate the impact of fibre inclusion on the overall sensory characteristics and the palatability of the cake. The results are presented in Figure 6.

Overall, no significant differences were found between CC and FeC in terms of hedonic and taste attributes. Similarly, there were no significant differences in flavour, except for the bran/cereal and egg flavours. Fibre enrichment resulted in an increased perception of bran/cereal flavour compared to the control (CC: give score out of 2, FeP: give score out of 3.29), while a significant decrease in egg flavour was observed (CC: give score out of 4.5 FeC: give score out of 3.38).

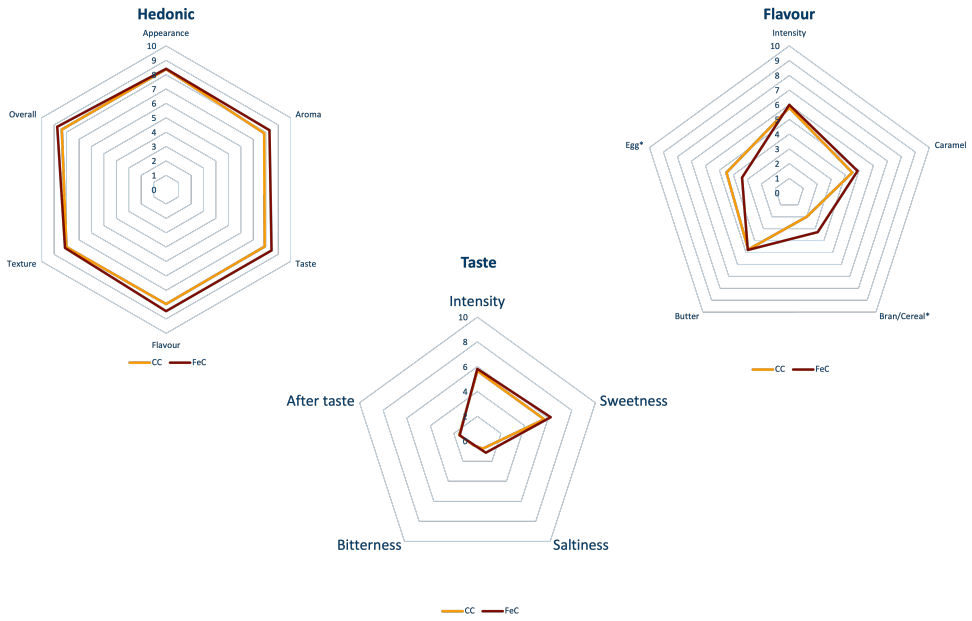


Figure 6. Descriptive sensory analysis of CC and FeC for hedonic, flavour and taste attributes. Results are represented on a spiderweb plot, attributes followed by * are significantly different ($p < 0.05$).

4 DISCUSSION

Developing a sweet product with an improved nutritional profile could support better diet adherence by satisfying cravings while aligning with dietary recommendations. By incorporating healthier ingredients and maintaining palatability, such products may help individuals sustain long-term dietary changes, reducing the risk of reverting to unhealthy eating patterns. By addressing the fibre gap and the demand for healthier sweet options in modern Western diets, this research underscores the importance of incorporating diverse fibre sources to maximise health benefits. Incorporating a variety of fibre types not only enhances the nutritional value of commonly consumed foods but also supports digestive health, cardiovascular function, and metabolic well-being. This study provides an in-depth analysis of the interactions between soluble fibres (SFC , GENU® Pectin, PromOat®), resistant starch (Fibersym® RW), and purified insoluble fibre (VITACEL L 600-30) within a cake matrix. Furthermore, the use of RSM resulted in the development of formulation with a blend of fibres that maintained the cake's quality while enhancing nutritional properties.

In this research RSM was utilised to characterise the impact of each fibre ingredient on fundamental cake characteristics. The inclusion of SFC in the cake matrix, even at low levels (0.5% flour replacement), resulted in higher bake loss due to the water-binding properties of the fibre, which release water during baking, increasing moisture evaporation (Pathania and Kaur, 2022). This contributed to a flatter profile in run 20, indicating that the fibre interfered with gluten development by competing for water, reducing

hydration and weakening the network. Correspondingly, the lower number of holes, indicates structural changes, possibly due to the effect of fibre on starch gelatinisation and gluten hydration, as reported by (Halm et al., 2024). Additionally, the reduced hardness and resiliance compared to the control confirmed changes in the gluten network, leading to a softer cake. Although research on isolated arabinoxylan is limited, studies on arabinoxylan-rich bran have shown positive effects on texture and structure, suggesting its potential to improve the quality of baked goods (Lebesi and Tzia, 2012; Moza and Gujral, 2017).

Among the individual fibre inclusions, Fibersym® RW resulted in the lowest hardness compared to the control formulation. This finding is consistent with literature reports, indicating either minimal impact or an improvement in structural and textural properties when resistant starch is incorporated (Hedayati et al., 2018; Ceylan et al., 2021). This may be linked to the lower predisposition of resistant starch to gelatinise and retrograde, processes which are known to have a significant impact on crumb texture (Li et al., 2024). PromOat® and VITACEL L 600-30 inclusion had the greatest impact on the specific volume, a characteristic which is usually negatively correlated to hardness (Pintaude, 2023; Sempio et al., 2024b). Specifically, the formulation containing PromOat® resulted in a cake with lower specific volume (-3.2%) and a higher hardness (+3.3%) and the formulation containing VITACEL L 600-30 resulted in a cake with higher specific volume (+7.7%) and lower hardness (-3.1%). A lower volume may result from the dilution of the gluten network within the mixture, weakening the network ability to trap carbon dioxide and limiting expansion (Struck, 2018). Conversely, a higher volume is associated with effective gas retention during baking (Gadallah et al., 2022). When the network remains strong and cohesive, it prevents gas from escaping, allowing the dough to rise properly. Instead, the inclusion of an insoluble fibre, which may introduce structural rigidity (Hachaichi et al., 2021), could at the same time promote a more open crumb structure, leading to greater volume and lower hardness. The inclusion of GENU® Pectin significantly altered crumb structure by increasing the number of cells and holes while reducing cell area and diameter. In run 17, the comparable specific volume to the control along with the loss of the typical dome shape may indicate that while the inclusion of GENU® Pectin facilitated the incorporation of air and increased the number of cells due to a possible higher viscosity (Halm et al., 2024; Li et al., 2021), it possibly compromised the structural integrity of the batter (Hosseini and Pazhouhandeh, 2023). This could be attributed to an imbalance between gas retention and the ability of the batter network to support uniform expansion, leading to reduced leavening capacity and a flatter profile.

In addition to evaluating the performance of individual fibre ingredients within the cake matrix, the RSM experimental design offered valuable insights into interactions between different fibre types. When comparing the effects of different fibre combinations, it was observed that both soluble-soluble and insoluble-insoluble fibre pairings positively influenced crumb texture by reducing hardness. However,

formulations containing soluble-soluble fibres (SFC , GENU® Pectin and PromOat®) exhibited either no change or a decrease in specific volume, whereas those with insoluble-insoluble fibres (Fibersym® RW and VITACEL L 600-30) resulted in an increased volume. Finally, formulations containing insoluble-soluble fibre combinations exhibited specific volume and hardness comparable to the control (no fibre inclusion). However, this combination significantly increased the number of holes in the crumb structure.

Based on the data obtained and considering the targeted parameters of maximum specific volume and fibre concentration, low hardness and number of holes, an optimal fibre-enriched formulation was developed using a tailored combination of SFC , Fibersym® RW , GENU® Pectin , PromOat® , and VITACEL L 600-30 . The cake products were analysed using two DF methods: AOAC 991.43, a widely used traditional method, and AOAC 2017.16, a more recent and comprehensive approach (Sempio et al., 2024a). This allowed for a comparison of fibre content results obtained by established versus updated analytical techniques. The resulting cake had a DF content which meets the EU Regulation of "source of fibre" based on the AOAC 2017.16 and "high in fibre" based on the AOAC 991.43 (European Parliament, 2006). The observed disparities in HMWDF results between AOAC 2017.16 and 991.43 methods stem from methodological differences in fibre recovery and scope. The 2017.16 method's broader detection of resistant starches and SDFS explains its higher baseline values for the CC compared to the the 991.43 method. However, the increase of fibre concentration in the FeC under 991.43 suggests the added fibre aligns with the older method's strengths (Sempio et al., 2024a). AOAC 991.43, optimised for traditional insoluble fibres (including cellulose and resistant starches), likely recovers it more efficiently, particularly in lipid-rich matrices where 2017.16's protease treatment or ethanol precipitation may underperform. This highlights the importance of method-fibre compatibility, where newer protocols capture diverse fibre types, while older methods remain effective for insoluble additives.

The quality of the batter is crucial in determining the final cake's texture and overall quality. Key factors such as consistency, viscosity, and air retention during mixing directly influence expansion, crumb structure, and moisture retention in the finished product (Yazici and Ozer, 2021; Shao et al., 2015). A well-structured batter supports effective leavening, yielding a uniform, light, and tender crumb (Fellows, 2022; Hu and Meng, 2024; Shao et al., 2015). The similar temperature at the inflection point suggests that major structural transitions, including protein denaturation and starch gelatinisation, occurred at comparable stages during baking, regardless of fibre inclusion. To our knowledge this type of test has not previously been applied to investigate the effects of dietary fibre addition on batter properties, with other studies focused primarily on characterising the effects of added proteins. However, the batter's viscosity increased nearly fivefold, indicating that while fibre incorporation significantly altered the rheological properties (Halm et al., 2024), it did not disrupt the fundamental thermal transitions within the cake matrix.

These findings support the structural modifications and variations in hardness previously observed in the RSM runs. Furthermore, they align with the final cake analyses, reinforcing the role of fibre inclusion in shaping textural properties.

Quality assessment of cake is key for a comprehensive insight into texture, structural integrity, and overall performance. The bake loss observed during the baking process provides insight into the moisture retention capacity of the formulation, reflecting the ability of the cake matrix to retain water and maintain structural integrity under thermal processing conditions (Tao et al., 2024). Bake loss in the FeC formulation was slightly lower, reflecting the trends observed in the RSM runs. However, the difference was not statistically significant, which is consistent with the study's objectives. Similarly, specific volume showed a slight decrease and hardness increased slightly, but there were no significant differences between the FeC and CC samples in either evaluation. This could be attributed to the improvement of air entrapment due to the higher viscosity of the batter (Yazici and Ozer, 2021), as well as the inclusion of resistant starch, which reduces the amount of starch available for gelatinisation and retrogradation (Ashwar et al., 2017), thereby influencing the textural properties of the final product. The altered behaviour of starch granules is confirmed by SEM micrographs, where FeC does not exhibit exposed gelatinised starch granules, in contrast to CC. Additionally, as previously hypothesised, this increase in viscosity had a more pronounced effect on crumb structure, leading to a greater number of cells and holes while reducing cell area and diameter (Halm et al., 2024). Specifically, soluble fibres have been reported to increase viscosity by binding water and interacting with the gluten network (Aydogdu et al., 2018; Ashwini et al., 2009; Horstmann et al., 2018), which may explain the observed structural changes. In contrast, insoluble fibres can disrupt the gluten network, potentially limiting expansion and modifying crumb porosity (Aydogdu et al., 2018). The inclusion of an optimised fibre mixture, carefully balanced to mitigate these effects, plays a crucial role in determining the final cake's texture and volume.

Mould growth on the cake crumb was monitored to evaluate shelf life and provide insights into the kinetics of mould development over time. The microbial shelf-life analysis indicated that mould growth began on day 9 in the CC formulation, whereas it was delayed until day 22 in the FeC formulation. This could be linked to the combined effect of high sugar content, which reduces water activity compared to products such as bread, and limits microbial growth (Van der Sman and Renzetti, 2021), and the partial replacement of easily digestible carbohydrates with fibre. Additionally, the change in structure due to the fibre ingredients inclusion could be responsible for a change in the aeration required for the microbial growth (Sempio et al., 2024b).

The in vitro simulation of starch digestion is essential for understanding the nutritional properties and potential glycaemic response of the final product. The fibre inclusion may have resulted in a reduction in

sugar release during FeC simulated digestion compared to the CC. This result is consistent with other studies that have shown that incorporating a variety of fibres in meals reduces glucose release, both under *in vivo* and *in vitro* conditions (Brennan et al., 2012; Huang et al., 2021; Sempio et al., 2024b, 2025). Moreover, European Food Safety Authority (2010) recognised that pectin consumption has been shown to reduce post-prandial glycaemic responses (Paulionis et al., 2015), due to its gel-forming properties.

The sensory analysis highlighted a desirable performance of the fibre ingredients incorporated into the cake product. No significant differences in the hedonic and taste attributes of the CC and FeC cakes were observed. Cake products appear to be an ideal matrix for incorporating purified fibre ingredients, as studies have demonstrated that consumers are willing to accept such products (Curutchet et al., 2021; Guedes et al., 2021). Within the flavour attributes, the FeC formulation exhibited an increase in the bran/cereal notes and a decrease in the egg flavour. This aligns with findings on composite flours, which have been reported to moderate or mask taste profiles (Donkor-Boateng et al., 2024). Although the FeC samples exhibited a significantly higher number of holes, sensory texture did not differ appreciably. Moradi et al. (2025) noted that fibre increased moisture retention minimized perceived texture alteration by the panellist. A broader review of porous crumb structure suggests that consumers are generally insensitive to modest porosity increases when crumb moisture and elasticity are preserved (Rathnayake et al., 2018).

In contrast to other food matrices such as bread or biscuits, the inclusion of fibre ingredients in the cake matrix appeared to have a more limited interaction with other components (Sempio et al., 2024b; Boudrag et al., 2025; Verbeke et al., 2024). This is supported by the fact that most of the evaluated characteristics did not exhibit statistically significant differences compared to the control, suggesting that the cake system may buffer or compensate for the structural and functional disruptions typically associated with fibre addition. Overall, the inclusion of fibre ingredients influenced the cake batter properties but did not significantly affect key characteristics of the final product, such as bake loss, specific volume, and hardness. Moreover, fibre enrichment had a positive impact on shelf-life, *in vitro* RSR, and sensory attributes.

5 CONCLUSIONS

Fibre fortification in refined white products is essential to improving fibre intake in Western diets. This study explored the impact of five DF ingredients in a cake matrix, optimising their combination through RSM to maintain quality similar to the control formulation. Techno-functional and sensory analysis confirmed similar overall acceptability, demonstrating that fibre enrichment can enhance nutritional value without compromising texture or taste. Notably, the fibre-enriched cake exhibited a reduced rate of reducing sugar release during in vitro digestion, indicating a potential for improved glycaemic response.

By employing both traditional and updated analytical methods, these findings facilitate direct comparisons with prior research, bridging methodological gaps between older and newer studies in the field. These findings highlight the potential of fibre incorporation in baked goods, paving the way for future research on its long-term

textitin-vitro and *in-vivo* effects on gut health, satiety, and dietary adherence.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualisation, J.W. and E.K.A.; experimental design, E.K.A. and R.S; data collection, R.S.; data analyses, writing—original draft preparation, R.S.; review and editing, L.N., E.Z, J.W. and E.K.A.; project administration, E.Z. All authors have read and agreed to the published version of the manuscript.

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DECLARATIONS

Ethics statement. This study was conducted according to established ethical guidelines for sensory evaluation. Informed written consent was obtained from all participants prior to their participation. The study received ethical approval from Social Research Ethics Committee (SREC), with approval number 2023-184. The study complies with all relevant regulations of University College Cork, Cork, Ireland.

Declaration of generative AI and AI-assisted technologies in the writing process. During the preparation of this work the author used Perplexity AI in order to improve the readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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