

Article

The Use of Bamboo Fiber in the Production of High-Fiber, Low-Carbohydrate, and Gluten-Free Bread: Physicochemical and Spectroscopic Properties

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Abstract: This study aimed to investigate the effect of adding bamboo fiber on the basic physical properties of gluten-free and low-carbohydrate bread. The control bread was made from buckwheat, flax, and walnut flour. Bamboo fiber was introduced to the bread recipe in proportions ranging from 0 to 10% (every 2%). The results showed that adding from 4 to 6% bamboo fiber to the control bread resulted in a slight rise of around 3% in volume, but a larger addition resulted in a drop in volume. The pH changes were also not significant; after more than 6% addition, the pH increased by about 2%. After adding more than 4% fiber, the color of the crumb changed noticeably ($\Delta E > 3$), owing mostly to a significant increase in the lightness (L^*) coefficient. The incorporation of the fiber had the greatest impact on the textural parameters when the storage time was increased to 48 h. The addition of 6% fiber resulted in unfavorable alterations in the hardness. In conclusion, our findings demonstrate that bamboo fiber can serve as a beneficial component for enriching gluten-free and low-carbohydrate bread, but its proportion should not exceed 4%. This developed bread with 4% addition of bamboo fiber can be classified as a functional bread for special diets; in addition to its very low carbohydrate content (15.3%), it was also characterized by a high fiber content (12.2%) and a low caloric value (176.7 kcal/100 g FM).

Keywords: bamboo fiber; gluten-free bread substitution; fiber-rich diet; crumb texture; FTIR spectroscopy



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1. Introduction

Gluten-free bread is essential for many people suffering from gluten intolerance, including those with celiac disease, wheat allergies, gluten ataxia, and non-celiac gluten sensitivity. It is also becoming a dietary trend among ordinary consumers. Because of the above, scientists have experienced difficulty in developing bread that stands out for certain features, such as an enhanced fiber content [1]. Dietary fiber is an essential component of our diet and may have a crucial role in the development of gluten-free bread. Furthermore, epidemiological studies have shown that a fiber-rich diet helps prevent various lifestyle diseases by acting as a prebiotic, shaping the composition of the gut microbiota [2]. Dietary fibers, from a technological point of view, can enhance the texture, shelf-life, via retarding staling, and sensory qualities of baked goods due to their water-binding capacity, gel-forming ability, and fat-mimicking and thickening properties [3]. Importantly, more insoluble fibers are used for texturizing and stabilizing purposes [4].

The recommended daily intake of dietary fiber varies internationally, with guidelines suggesting 30 g per day in the EU and UK and 28 g per day in the US [5].

Bamboo is a giant grass belonging to the subfamily *Bambusoideae* of *Poaceae*. It is one of Earth's oldest and fastest-growing plants, naturally occurring in the tropical, subtropical, and temperate regions of all continents except Europe [6,7]. Fresh shoots, composed of 90% water, primarily provide fiber (6–8 g per 100 g) and protein (1.49–4.04 g per 100 g) as key nutrients, with less than 2% being contributed by other nutrients [8]. Bamboo shoot dietary fibers are predominantly insoluble (around 92%), with the main carbohydrate contributors being insoluble fibers such as cellulose, hemicellulose, and lignin, which play a crucial role in their nutritional profile. In comparison, only about 8% of the fibers are soluble [9,10]. The fiber content in bamboo shoots rises as they mature or undergo processes like canning and fermentation. In the past decade, components from bamboo shoots, such as dietary fibers, have been extracted, purified, and utilized to develop functional products [10]. Bamboo fiber is commercially available as a white, odorless powder with a neutral taste and at least 95% fiber. This type of fiber can be a valuable ingredient that improves the overall health benefits of fish balls [11], meat products [12], yoghurt [13], cookies [14], and biscuits [15]. In Brazil, bamboo fiber has been incorporated into gluten-free products like bread, toast, and more, targeting a specific consumer market that has developed recently [16]. The research conducted by Park and Jhon [9] demonstrated that incorporating a high-fiber diet with bamboo shoots has positive impacts on reducing total cholesterol levels (LDL fraction) and the atherogenic index, which significantly improved bowel function in healthy young women. Consequently, the findings imply that an increased intake of bamboo shoots, rich in dietary fiber, could contribute to the prevention of chronic illnesses. As Zhang et al. [17] reported, insoluble dietary fiber (IDF) shows potential in preventing type 2 diabetes due to its functional and physicochemical properties, including the ability to adsorb glucose and enzymes, inhibit starch hydrolysis, and reduce oxidative stress. It is also worth mentioning that research conducted by Felisberto et al. [7] demonstrated that flour made from young bamboo culm shoots can be used, either in its full or purified form, as a fiber source due to its technological and physicochemical properties, which are comparable to other high-fiber ingredients. The findings revealed that the chemical composition and technological properties of the fractions derived from young bamboo culm shoots varied and could lead to the development of new high-fiber ingredients, characterized by a yellowish color and favorable WSI and WAI properties, facilitating their incorporation into bakery and pasta products.

So far, no formulation has been developed for a low-carbohydrate and gluten-free bread with an increased fiber content incorporating the insoluble fraction of bamboo fiber. Existing research focuses solely on the physicochemical properties of traditional wheat bread enriched with bamboo fiber. Moreover, current consumer trends favor products with a “clean label”, which challenges bakers to create a product that not only meets these expectations but also positively impacts consumer health.

For the reasons mentioned above, the objective of this study was to evaluate the physicochemical and spectroscopic characteristics of gluten-free, low-carbohydrate, and fiber-rich bread as a new functional food recommended to different groups of consumers.

With a view to further characterizing the samples in terms of their physicochemical properties, a spectral FTIR analysis (Fourier-transform infrared spectroscopy) was conducted. The analysis of the FTIR spectra allowed for a detailed description of the products at a molecular level and an evaluation of the used additive's impact on the spectral shift and intensity of bands characteristic of respective notable functional groups present in the food products. The observed significant changes in spectral intensity can be associated with

improvements in the specific physical/quality properties of the product, which suggests its potential industrial viability.

2. Materials and Methods

2.1. Materials

In our study, the basic bread recipe consisted of flaxseed (Bio Planet, Gniezno, Poland), buckwheat (Helcom, Kraków, Poland), and walnut flour (OlVita, Myslakow, Poland). The bread composition also included psyllium (Dimica, Koszyce, Slovakia), guar gum (Bio Planet, Gniezno, Poland), dried yeast (LeSaffre, Maisons-Alfort, France), and Himalayan salt as additives. The bamboo fiber (MK Nutrition, Stargard, Poland) was obtained from a health food store.

2.2. Bread Preparation

The recipe for the control bread (Table 1) was based on three types of flour: flaxseed, buckwheat, and walnut with a percentage share of 42.5, 42.5, and 15%, following the formulation developed by Wójcik et al. [18]. The bamboo fiber was added in a proportion ranging from 2 to 10% by weight of all-gluten-free flour. Bamboo fiber replaced the main gluten-free flours (flaxseed and buckwheat). Other technological additives were in used the following amounts: psyllium (4%), guar gum (2%), salt (2%), dried yeast (1%), and water (dough yield: 250–270%). After combining all the ingredients with water, the dough was kneaded in a laboratory mixer (CLATRONIC KM 3630, Kempen, Germany) for 5 min (at 100 rpm for 2 min and 200 rpm for 3 min). In the next step, the dough was divided into 116 g pieces, gently shaped by hand, rounded, and placed in rectangular molds (96 × 60 mm top; 80 × 50 mm bottom; 40 mm deep). The fermentation process was carried out for 60 min at 30 °C (75–80% relative humidity), and then the loaves were baked in a baking oven (Sadkiewicz Instruments, Bydgoszcz, Poland) at 225 °C for 20 min. The bread loaves were allowed to cool at ambient temperature and then sealed in polyethylene bags and stored for 24 h before the assessment of the texture parameters.

Table 1. Gluten-free and low-carbohydrate bread recipes used in the study.

Ingredients (g)	Recipes					
	I-BF0%	II-BF2%	III-BF4%	IV-BF6%	V-BF8%	VI-BF10%
Buckwheat flour	42.5	41.5	40.5	39.5	38.5	37.5
Flaxseed flour	42.5	41.5	40.5	39.5	38.5	37.5
Walnut flour	15	15	15	15	15	15
Bambo fiber	-	2	4	6	8	10
Guar gum	2	2	2	2	2	2
Psyllium	4	4	4	4	4	4
Yeast	1	1	1	1	1	1
Salt	2	2	2	2	2	2
Water			150–170 mL			

2.3. Basic Properties of Bread

A few hours after the baking was completed, the volume of the loaves was measured using a method based on millet seeds, according to the procedure described by de Erive et al. [19]. The volume was determined in the vessel by measuring the volume of displaced millet seeds by the tested loaf of bread. The volume measurements were repeated 3 times for each bread sample, the difference between the bread's mass was calculated before and after baking (as a percentage) to determine the baking loss. The pH of the breadcrumbs was measured using a 206-ph2 pH meter (Testo, Pruszków, Poland). The pH meter was calibrated using buffer solutions, and the measuring probe was placed in a slice of bread

about 15 mm thick. The room was free from foreign odors. The pH measurement was performed in 3 repetitions.

The fundamental composition of the gluten-free bread was evaluated following the AACC standards (AACC) [20]. Protein (PR), fat (Method 30-10.01), total dietary fiber (TDF) (Method 32-05.01), and available carbohydrates [21] were analyzed.

2.4. Color Measurements of Bread

The color of the breadcrumbs was assessed using a CR 30-16 colorimeter (Precise Color Reader, 4Wave, Tychy, Poland) operating according to the CIE Lab* color system. In this system, L* represents the color lightness (from 0 to 100), a* indicates red/green values (from −150 to +100), and b* corresponds to blue/yellow values (from −100 to +150). The total color difference (ΔE) between the control gluten-free and BF-enriched breads was determined [22]. Each measurement was conducted three times. ΔE was calculated using the following formula:

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2}$$

2.5. Texture Properties of Bread

The texture properties of the breadcrumbs were evaluated using the TPA test at 24 and 48 h post-baking. The test samples (15 mm thick) were cut from the central part of a thick bread slice using a 28 mm diameter knife cutter. The measurement was performed using a ZWICK Z020/TN2S testing machine (Zwick Roell Group, Ulm, Germany). The samples were compressed twice to 60% of their original height at a speed of 20 mm/s using a 25 mm diameter piston. The device was operated with a load force of up to 100 N. In the testXpert V 7.1 simulation software, two compression curves were obtained from the analysis, from which the following texture parameters were calculated: hardness, cohesiveness, springiness and, chewiness [23]. Each measurement was repeated eight times.

2.6. Infrared Spectra Measurements

The FTIR spectra of the samples were acquired with an IRSpirit spectrometer (Shimadzu, Kyoto, Japan), outfitted with a ZnSe-based ATR (attenuated total reflection) module. The ZnSe crystal, designed with a 45° geometry, enabled the optimal measurements by promoting multiple internal reflections of the laser beam, with each sample undergoing 40 scans. The spectrometer software automatically averaged the spectral data collected. To ensure the crystal remained contaminant-free, ultrapure solvents sourced from Merck KGaA (Darmstadt, Germany) were used for cleaning. Spectra were captured in the range of 450–3800 cm^{−1} and subsequently analyzed and processed using the Grams AI software (Version 9.3, ThermoGalactic Industries, Waltham, MA, USA) and OriginPro 2021b (Version SR1, 9.8.5.204, OriginLab Corporation, Northampton, MA, USA). The samples prepared for FTIR measurements were dried and ground in a rice mill. The appropriately prepared samples, each weighing 1 mg, were placed on the crystal surface. A total of 40 scans were performed for each sample and subsequently averaged using the LabSolutions software v5.72 (Shimadzu, Kyoto, Japan). A special solid-sample accessory, provided with the spectrometer by Shimadzu, was used for the measurements.

2.7. Caloric Value of Bread

The caloric content of both the control bread and the bread with the optimal BF addition was assessed following the methodology outlined by Costantini et al. [24], using the Atwater coefficients. The caloric value was determined using specified energy factors (9 for fats, 4 for carbohydrates, 4 for proteins, and 2 for fiber) for 100 g of fresh bread. Otherwise, one gram of fats, carbohydrates, proteins, or fiber provides 9, 4, 4, and 2 kcal, respectively.

2.8. Statistical Analyses

Statistical analysis was conducted using ANOVA with the STATISTICA 12.0 software (StatSoft, Cracow, Poland), followed by Tukey's test to evaluate the significance of differences at a level of $\alpha = 0.05$. The breads were baked from the same raw material in three repetitions. The research design was random—first, the breads were tested in the range from 0 to 20%, but above 10%, the changes in bread quality were very unfavorable, so the tests were finally carried out in the range up to 10%. All measurements were performed in triplicate, and means and standard deviations were calculated. Different outcomes are marked with different lower case letters (a, b, c, ...) and upper case letters (A, B, C, ...) where the influence of two factors was studied.

3. Results and Discussion

3.1. Basic Properties of Gluten-Free Bread with Different Amounts of BF

Table 2 presents the basic properties of the obtained loaves of bread enriched with bamboo fiber. The baking loss of the tested bread ranged from 9.8% to 11.2%. The loaves of bread with BF added above 4% showed a slightly higher baking loss of 11.1% compared to the control bread, in which the baking loss was approximately 9.8%.

Table 2. Basic properties of gluten-free and low-carbohydrate bread fortified with bamboo fiber (BF).

Addition of BF (%)	Baking Loss (%)	The Specific Volume of Bread ($\text{cm}^3 \cdot \text{g}^{-1}$)	pH (-)
0	9.85 ± 0.35^a	1.62 ± 0.01^a	5.15 ± 0.03^a
2	9.97 ± 0.31^a	1.62 ± 0.02^a	5.18 ± 0.01^a
4	10.37 ± 0.22^a	1.66 ± 0.01^b	5.19 ± 0.01^a
6	10.91 ± 0.26^b	1.67 ± 0.01^b	5.26 ± 0.02^b
8	11.25 ± 0.22^b	1.60 ± 0.01^a	5.25 ± 0.01^b
10	11.20 ± 0.49^b	1.60 ± 0.01^a	5.26 ± 0.02^b

Values within the same column followed by superscript letters ^{a,b} show significant differences ($\alpha = 0.05$) ($n = 3$). Mean $\pm$ SD.

In comparison with the baking loss data obtained in our previous studies [18,25], where low-carbohydrate loaves of bread were fortified with pea protein powder (baking loss of about 27%) or walnut flour (baking loss of 13%), the values obtained in the present studies were lower. This could be due to the presence of an insoluble bamboo fiber fraction in the composition of the bread, which absorbs and retains water very well [4]. It was also observed that the addition of bamboo fiber above 4% caused an increase in volume (from 1.62 to 1.66 and 1.67 cm^3/g), while with additions of 8% and 10%, a decrease in volume was observed up to the level of 1.60 cm^3/g . According to Kučerová et al. [26], adding wheat, apple, and potato fiber (higher soluble fiber content) to bakery products caused a decrease in their specific volume. However, with the addition of bamboo fiber, which does not contain any soluble fiber, in contrast to the other tested fiber fractions, a higher specific volume was observed for wheat bread enriched with 3% compared with the sample with 1% bamboo fiber. On the other hand, Martínez et al. [27] indicated that potatoes, peas, oats, and bamboo, which contain high amounts of insoluble dietary fiber, increased the dough consistency and reduced the dough rising, which is directly related to a lower bread volume. Gluten-free bread with added fiber typically has a lower volume; however, if soluble or fine insoluble fibers are present, they might diminish the dough consistency while increasing the volume after fermentation. Such soluble fibers combine with the hydrocolloid in the water phase, promoting the formation of a film that covers the starch granules, providing greater structural stability [27]; however, with a higher proportion of fibers as well as a constant proportion of hydrocolloid in gluten-free bread recipes, the

structure can be disrupted, resulting in a lower volume. In the case of the pH value of the crumb, it was observed that increasing the amount of bamboo fiber added caused a slight increase from 5.15 to 5.27. The obtained crumb pH values indicate that the bamboo fiber did not undergo chemical reactions with the other ingredients, nor did it affect the acid–base balance upon its inclusion in the proposed gluten-free bread recipe.

3.2. Crumb Color of Gluten-Free Bread with Different Amounts of BF

Upon analyzing the color parameters of the obtained breadcrumb (Table 3, Figure 1), an increase in the L^* value from 35.2 to 38.2 was observed. In the case of the remaining color components a^* and b^* , no significant changes in these values were observed. The control bread's crumb showed a dark brown color, likely due to the presence of flaxseed flour in the basic recipe, which has a naturally darker shade due to pigments found in the outer seed coat. The used bamboo fiber MK Nutrition has a light white color and an odorless smell. As a result, the total color difference (ΔE) increased from 1.16 to 5.03. A similar finding was made for the color of cookies fortified with young bamboo culm flour, where Felibersto et al. [16] found that that kind of flour had a high lightness value ($L > 80$), indicating a light color that does not impact the final product's color, making it suitable as a fiber-rich ingredient.

Table 3. Color parameters of gluten-free breadcrumbs fortified with BF.

Sample	L^*	a^*	b^*	ΔE
0	35.21 ± 0.07^a	8.21 ± 0.01^a	24.60 ± 1.07^a	-
2	35.73 ± 0.70^a	8.22 ± 0.02^a	23.82 ± 0.15^a	1.16 $\pm 0.11^a$
4	38.30 ± 0.22^b	8.51 ± 0.10^a	23.41 ± 0.22^a	3.06 $\pm 0.12^b$
6	38.31 ± 0.11^b	8.44 ± 0.03^a	23.64 ± 0.14^a	3.17 $\pm 0.09^b$
8	38.15 ± 1.21^b	8.43 ± 0.22^a	23.72 ± 0.11^a	3.50 $\pm 0.14^b$
10	38.22 ± 0.37^b	8.32 ± 0.03^a	23.60 ± 0.20^a	5.03 $\pm 0.12^c$

Values within the same column followed by superscript letters ^{a–c} show significant differences ($\alpha = 0.05$) ($n = 3$). Mean $\pm$ SD.



Figure 1. Appearance of bread with different amounts of BF (from the left, the control bread, and then with 2, 4, 6, 8, and 10% BF addition).

3.3. Texture Parameters of Gluten-Free Bread with Different Amounts of BF

The hardness of the breadcrumbs with the addition of bamboo fiber (Table 4) after 24 h of storage was at a similar level to the control sample (on average, approx. 42 N), except for the sample with 10% bamboo fiber (46.2 N).

An increase in the hardness value of the crumb was observed after 48 h of storage. This is a typical phenomenon associated with the staling of breadcrumbs. The smallest difference in the change in hardness was observed for the samples with 2 and 4% additions of BF. As reported by Sabanis et al. [28], the addition of cereal fiber like oat, barley, and maize to gluten-free bread, except for wheat fiber, resulted in a softer crumb than the control bread on the first day and for three days after baking. Research by Pichler et al. [29] suggests that adding micronized oat husk fiber to a gluten-free bread recipe slightly increased the crumb firmness, with larger amounts leading to only minimal further increases, regardless of the baking method used. Increasing the amount of bamboo fiber added did

not cause any significant changes in the cohesiveness. After 24 h from the end of baking, the cohesiveness value ranged from 0.36 to 0.38, and after 48 h, from 0.31 to 0.40. However, Chockchaisawasdee et al. [30] reported in their study that the addition of faba bean husk as a fiber supplement, which was introduced to the recipe in a range from 5–15% and with different particle sizes, increased the cohesiveness compared to the control sample. On the other hand, Rinaldi et al. [31] analyzed the effect of the cocoa bean fiber particle size, at a concentration of 4 g/100 g of the mixture, on the texture of gluten-free bread and showed that the particle size did not affect the hardness or cohesiveness of the breadcrumbs. In our study, the most beneficial effect of the fiber on the texture parameters, i.e., hardness and cohesion 48 h after baking, was noted with a maximum of 4% addition of BF. Concerning the springiness of the breadcrumb after 24 h of storage, no significant changes in the value of this parameter were observed. However, after a longer storage time (after 48 h), it was noted that the addition of BF above 2% caused a small but statistically significant increase in springiness (on average, by 0.05). However, the chewiness value 24 h after baking was at a similar level for all the tested samples (approx. 12 N), except for the breadcrumbs with the highest 10% share of BF, where the value of this parameter was 2 N higher. After 48 h of storage, an increase in chewiness was observed only for the bread enriched with bamboo fiber, which was, on average, by 2.6 N.

Table 4. Texture properties (hardness, cohesiveness, springiness, chewiness) of gluten-free breadcrumbs fortified with bamboo fiber (BF).

Addition of BF (%)	Hardness (N)	After 24 h Cohesiveness (-)	Springiness (-)	Chewiness (N)
0	41.71 ± 0.25 ^{aA}	0.36 ± 0.03 ^{aAB}	0.75 ± 0.02 ^{aAB}	11.28 ± 0.12 ^{aA}
2	42.90 ± 0.58 ^{aA}	0.36 ± 0.02 ^{aB}	0.77 ± 0.01 ^{aB}	12.22 ± 0.22 ^{bB}
4	42.52 ± 0.55 ^{aA}	0.38 ± 0.04 ^{aBC}	0.73 ± 0.03 ^{aA}	12.50 ± 0.31 ^{bB}
6	42.32 ± 0.38 ^{aA}	0.37 ± 0.01 ^{aB}	0.73 ± 0.01 ^{aA}	12.50 ± 0.21 ^{bB}
8	42.84 ± 0.61 ^{aA}	0.38 ± 0.05 ^{aBC}	0.76 ± 0.02 ^{aAB}	12.12 ± 0.15 ^{bB}
10	46.24 ± 0.61 ^{bB}	0.37 ± 0.05 ^{aB}	0.78 ± 0.05 ^{aB}	14.11 ± 0.05 ^{cC}
After 48 h				
0	51.21 ± 0.45 ^{aC}	0.31 ± 0.02 ^{aA}	0.71 ± 0.04 ^{aA}	11.20 ± 0.13 ^{aA}
2	44.80 ± 0.36 ^{abB}	0.32 ± 0.03 ^{aA}	0.73 ± 0.03 ^{aA}	15.22 ± 0.21 ^{bC}
4	46.93 ± 0.24 ^{bB}	0.35 ± 0.02 ^{aAB}	0.81 ± 0.02 ^{bBC}	15.31 ± 0.12 ^{bC}
6	54.32 ± 0.42 ^{aD}	0.40 ± 0.02 ^{bC}	0.82 ± 0.02 ^{bBC}	15.63 ± 0.11 ^{bC}
8	51.84 ± 0.26 ^{aC}	0.40 ± 0.06 ^{bBC}	0.78 ± 0.01 ^{abB}	14.91 ± 0.09 ^{bC}
10	52.10 ± 0.26 ^{aC}	0.39 ± 0.06 ^{abBC}	0.82 ± 0.01 ^{bC}	15.63 ± 0.09 ^{bC}

^{a–c}: values in the same column measured at the same time after baking marked with different letters are significantly ($\alpha = 0.05$) different. ^{A–D}: letters showing significant ($\alpha = 0.05$) ($n = 3$) differences between the texture parameters determined at different times (24 or 48 h) after baking. Mean ± SD.

3.4. FTIR Spectroscopic Analysis of Gluten-Free Bread with Different Amounts of BF

Figure 2 presents the spectra obtained with the FTIR method for the samples of low-carbohydrate bread with the addition of bamboo fiber at a concentration of between 0 and 10%, as described above. The study conducted with the use of FTIR spectroscopy facilitated an in-depth molecular analysis of the samples, with a particular focus on characterizing the primary bands corresponding to the particular ingredients of the product. One should note that the main advantage of the selected ATR technique stems from the simplicity of the required sample preparation as well as the ability to perform solid-state measurements directly, which eliminates the need for grinding the samples with potassium bromide or ionide, thus consequently minimizing the risk of contamination or structural alteration of the samples. In addition, while alternative methods may facilitate deeper penetration into the sample, in the case of the materials considered in this study, the selected technique

proved entirely sufficient. For the sake of clarity, the results in Table 5 are presented, indicating the locations of the main bands and associating the same locations with the corresponding vibrations of particular functional groups.

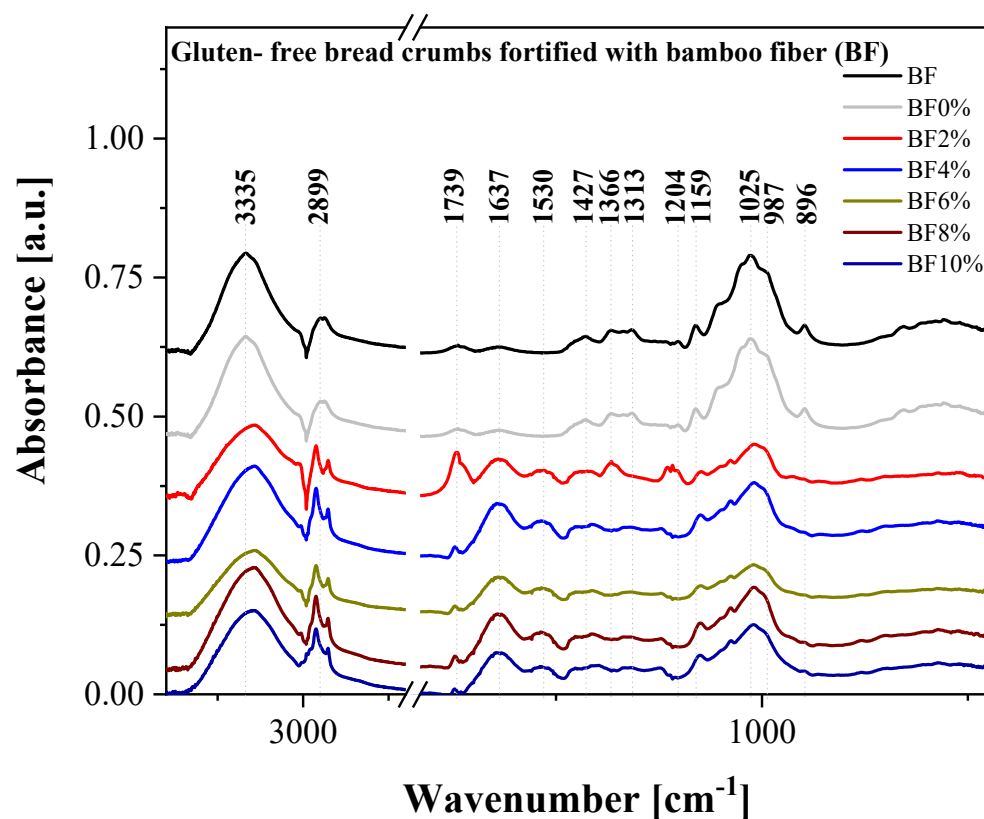


Figure 2. FTIR spectra of the gluten-free bread crumbs with bamboo fiber (BF).

As follows from the literature [32], the first band with the maximum at ca. 3335 cm^{-1} is associated with the stretching vibrations of hydroxy (-OH) groups [33]. Notably, in the samples of low-carbohydrate bread, the band was shifted by approx. 50 cm^{-1} towards lower frequencies as compared to bamboo fiber alone. The intensity of this band also changed, with the highest intensity observed for pure bamboo fiber. Said effects can be associated with molecular interactions between the base product and the additive, which entailed the formation of strong hydrogen bonds—a phenomenon that seems to naturally occur in food samples of this type. Furthermore, as follows from the literature, bamboo fibers are characterized by considerable hygroscopicity, which may be reflected by the changing intensity of the band, both relative to the bamboo fiber itself and in the entire spectrum range analyzed [34]. The bands located at 2930 cm^{-1} and 2853 cm^{-1} are associated with stretching vibrations of the C-H groups in -CH_2 systems. We observed interesting changes in the case of the band peaking at 1738 cm^{-1} , which corresponds to the stretching vibrations of the carbonyl C=O group. The band was the most intensive in the samples containing 0% bamboo fiber, whereas above 2%, the intensity dropped virtually to zero. Although initially surprising, the effect can be explained by the (increasing) presence of the mentioned hydrogen bonds in the samples; the growing percentage content of the additive molecules created more opportunity for interaction, i.e., the formation of such hydrogen bonds between the ingredients. It is also noteworthy that the bread made of buckwheat, flax, and peanut flour was characterized by a relatively high protein content, which affected the intensity of said bands in the samples without the addition of bamboo fiber. In terms of the deformation vibrations of hydroxyl groups, a band emerged with a maximum intensity at 1640 cm^{-1} , which, in the samples of this particular type, is associated

primarily with the Amide I system, related to the secondary protein structure. The highest intensity in this range was observed for the sample without the addition of bamboo fiber (0%). One should bear in mind that Amide I vibrations include vibration components originating from $\nu(\text{C}=\text{O})$ and $\nu(\text{C}-\text{N})$ as well as deformation vibrations of $\delta(\text{N}-\text{H})$ [35,36]. In turn, the bands located in the 1533 cm^{-1} region correspond to the vibrations of Amide II structures, including deformation vibrations of $-\text{N}-\text{H}-$ groups, stretching of the $-\text{C}-\text{N}-$ group, and stretching of the carbonyl $\text{C}=\text{O}$ group [36]. As we continue to characterize the key bands, we should mention the vibrations with a maximum at 1412 cm^{-1} , which are also associated with the structural vibrations of proteins. Reports in the literature often additionally associate the same with deformation vibrations of the $-\text{CH}_2$ and $\nu(-\text{COO})$ groups, which is reflected by the highest intensity observed in the sample without the bamboo additive. The band peaking at 1217 cm^{-1} is characteristic of Amide III systems in protein structures and was also clearly visible in the samples containing no bamboo fiber. In this region, we observed C-N stretching, N-H deformation, and C-C stretching vibrations.

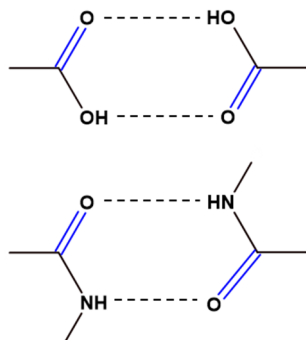
Table 5. The assignment of FTIR absorption bands, registered within the spectral range of $450\text{--}3800\text{ cm}^{-1}$.

FTIR Positioning of Band [cm^{-1}]	Types and Origins of Vibrations
3335	(<i>intra</i> -)molecular hydrogen bonding and $\nu(\text{O}-\text{H})$ in H_2O
2930	asymmetric and symmetric: $\nu(\text{C}-\text{H})$ in CH_2 and CH_3
2853	
1738	$\nu(\text{C}=\text{O})$ free and hydrogen-bound
1648	$\nu(\text{C}=\text{C})$ and Amide I and $\delta(\text{O}-\text{H})$ adsorbed H_2O
1533	$\nu(\text{C}=\text{C})$ and Amide II
1412	$\delta(\text{CH}_2)$, $\delta(\text{C}-\text{H})$ enhanced by $\delta(-\text{OH}$ in plane)
1367	$\delta(\text{O}-\text{H})$, but mainly $\delta(\text{C}-\text{H})$
1217	$\delta(\text{C}-\text{H})$ and asymmetric bridge oxygen stretching -OH in-plane bending and Amide III
1105	$\nu(\text{C}-\text{O}-\text{C})$ and strong $\nu(\text{C}-\text{O})$ and ring stretching modes and asymmetric in-phase ring stretching
1150	
1025	
984	β -linkage of cellulose/ring breathing and asymmetric out-of-phase stretching, -OH out-of-plane bending, and CH_2 rocking
760	
657	

ν —stretching vibrations, δ —deformation vibrations.

In the context of the relevant type of food samples, the bands occurring from 1151 cm^{-1} to ca. 900 cm^{-1} and related to the stretching vibrations of C-O and C-C groups in the C-O-C system are particularly interesting. The stability of the bands' intensity indicates that the level of the samples' crystallinity remained largely unchanged. It is noteworthy that the maximum at 1151 cm^{-1} was shifted by 10 cm^{-1} towards higher frequencies in the samples containing pure bamboo fiber. The vibrations around 895 cm^{-1} are also significant, as they correspond to the vibrations of sugar fractions forming the cellular walls of bamboo, i.e., cellulose, hemicellulose, pectin, and aromatic lignin polymers [32,37–39]. One should also underline that all the mentioned types of vibrations originated from the primary components of our samples, including cellulose formed through the merging of the linear chains of aldehyde sugars. The hydrogen bonds present in the cellulose structure allowed

for the formation of ordered crystalline areas, while random hydrogen bonds led to the formation of amorphous structures (an example of the strong hydrogen bond mechanism is presented in Scheme 1).



Scheme 1. Strong hydrogen bond.

Other noteworthy components present in our samples and contributing to the vibrations discussed included lignin and hemicellulose as well as proteins and lipids, which, although present in trace amounts, nonetheless produced relatively strong vibrations. The vibrations were the most intensive in the bamboo fiber samples, while the addition thereof to the primary samples triggered a significant decrease in the band's intensity or its complete decay. Similarly to the case of hydrogen bonds, the effect may indicate a better scattering of the molecules in the end product, which could potentially impact its quality.

3.5. Caloric Value of Gluten-Free Bread with Optimal Amount of BF

Taking into account the above-mentioned physicochemical parameters, particularly the texture of the bread after storage, which did not decrease significantly, the best rating was given to bread with 2 and 4% additions of bamboo fiber. The goal of our study was to increase the fiber content; thus, we included the nutritional values (Table 6) of the control bread and the bread with a 4% fiber content, which we considered optimal. The initial organoleptic study supported this; nevertheless, in the future, we intend to conduct more detailed analyses. The control bread and fiber-enriched bread formulas were characterized by a very low carbohydrate content (15.91 and 15.35%), while traditional wheat bread usually has this value higher than 70% [24]. The incorporation of 4% bamboo fiber improved the fresh bread's overall fiber content from 10.53 to 12.23%. According to current EU regulations, foods having more than 6% (6 g/100 g) fiber are categorized as high-fiber products.

Due to the high content of dietary fiber in the bread, it was also possible to reduce the caloric value of the product (176.7 kcal/100 g); most breads offered on the market have this value higher than 200 kcal [2,24].

Table 6. Chemical components and caloric value of gluten-free bread with optimal amount of bamboo fiber (BF).

Chemical Components (% FM)	Addition of BF (%)	
	0	4
Protein	15.01 ± 0.24 ^a	14.51 ± 0.21 ^b
Fat	3.78 ± 0.06 ^a	3.64 ± 0.04 ^b
Total fiber	10.53 ± 0.12 ^a	12.23 ± 0.12 ^b
Available carbohydrate	15.91 ± 0.38 ^a	15.35 ± 0.28 ^a
Caloric value (kcal/100 g)	179.21 ^a	176.70 ^b

Values in the same row followed by superscript letters ^{a,b} show significant differences ($\alpha = 0.05$) ($n = 3$). Mean ± SD.

4. Conclusions

This study supports the hypothesis that bamboo fiber may be added to gluten-free and low-carbohydrate bread without reducing its quality. The proposed recipe should contain a maximum of 4% bamboo fiber in addition to the following base ingredients: buckwheat flour (40.5%), flaxseed flour (40.5%), and walnut flour (15%). The spectroscopic FTIR analysis revealed significant differences between the samples, particularly between those containing bamboo fiber and the bread without the additive. The presence of bamboo fiber had a clear impact on the bread's composition by enriching its carbohydrate/polysaccharide structures. In turn, the bread prepared with buckwheat, flax, and peanut flour was characterized by a high content of protein structures, which was reflected by the intensity of the bands registered in the Amide I and Amide II regions. Additionally, the obtained products showed a greater degree of molecular mixing and ordering, which was confirmed by the shifting and lower intensity of the bands associated with the formation of hydrogen bonds—this may facilitate a more targeted applicability of the product. In our future studies, we plan to continue research into food products such as bread by employing spectroscopic methods, considering new potential additives, and identifying new marker bands to further broaden the analyses of relevant spectral structures, their properties, and associations with the functional properties of products.

In agreement with the assumptions made, this research yielded a suitable bread recipe with a very low carbohydrate level (15.35%) and a high fiber content (12.23%). In future studies, a sensory evaluation of this type of bread is recommended. It is expected that due to the neutral taste and an odorless smell, the addition of such a percentage will not negatively affect the sensory characteristics perceived by consumers. In future research, it is feasible to recommend changing the recipe to produce bread with superior physical qualities by using alternative hydrocolloids or enzymes. Another suggestion is to adapt this recipe to make bread with a higher protein content.

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