



Review

Delving into the Role of Dietary Fiber in Gluten-Free Bread Formulations: Integrating Fundamental Rheological, Technological, Sensory, and Nutritional Aspects

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Abstract: The evidenced relevance of dietary fibers (DF) as functional ingredients shifted the research focus towards their incorporation into gluten-free (GF) bread, aiming to attain the DF contents required for the manifestation of health benefits. Numerous studies addressing the inclusion of DF from diverse sources rendered useful information regarding the role of DF in GF batter's rheological properties, as well as the end product's technological and nutritional qualities. The presented comprehensive review aspires to provide insight into the changes in fiber-enriched GF batter's fundamental rheological properties, and technological, sensory, and nutritional GF bread quality from the insoluble and soluble DF (IDF and SDF) perspective. Different mechanisms for understanding IDF and SDF action on GF batter and bread were discussed. In general, IDF and SDF can enhance, but also diminish, the properties of GF batter and bread, depending on their addition level and the presence of available water in the GF system. However, it was seen that SDF addition provides a more homogenous GF batter structure, leading to bread with higher volumes and softer crumb, compared to IDF. The sensory properties of fiber-enriched GF breads were acceptable in most cases when the inclusion level was up to 7 g/100 g, regardless of the fiber type, enabling the labeling of the bread as a source of fiber.

Keywords: gluten-free; dietary fibers; soluble fibers; insoluble fibers; rheology; bread quality; sensory properties; texture; nutritional quality



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1. Introduction

Bakery products, as one of the basic food groups in the food pyramid, are an integral part of everyday meals. The basic raw material in bread production is wheat flour, whose proteins (gliadin and glutenin) form gluten during mixing in the presence of water. The resulting gluten matrix is responsible for dough elasticity and extensibility, as well as the ability to retain gases formed during fermentation, resulting in a recognizable end product with characteristic sensory properties and adequate volume [1]. However, in the portion of the population with insufficiently developed immune tolerance to gluten proteins, consumption of gluten-containing products causes gluten enteropathy (celiac disease) and other gastrointestinal problems. Celiac disease represents an immune-mediated food sensitivity with an autoimmune component [2] and a prevalence of almost 1% in the population worldwide [3]. Currently, the only safe and effective therapy for patients with celiac disease is a lifelong adherence to a gluten-free (GF) diet, which includes the withdrawal of cereal-based products and a daily gluten intake of less than 20 mg to avoid side effects and complications [4].

The production of GF bread is technologically more demanding, considering that the absence of gluten affects dough rheology, the production process, but also the end product quality. Compared to wheat dough, GF dough is less cohesive and elastic and

is more frequently referred to as batter [5]. GF batters are unable to retain the maximal quantity of gases formed during fermentation, resulting in a GF bread that is characterized by low specific volume, a dry and crumbly texture with reduced color intensity, and insufficiently pronounced taste and smell [6]. In an attempt to obtain a GF bread with similar physical properties as its wheat-based counterparts, apart from starches and GF flours, ingredients such as hydrocolloids, proteins, and enzymes were used with the main function of “mimickinG” gluten viscoelastic properties. Although, GF bread’s technological quality reached appropriate levels, the nutritional value of GF bread still represents a bottleneck in achieving a well-balanced GF diet [7].

GF bread produced with the use of different GF flour and starches essentially has a very low content of protein, dietary fiber (DF), vitamins, and minerals [8,9]. Conducted studies demonstrated the necessity for GF bread enrichment with DF and micronutrients, considering the low intake of fiber, iron, calcium, folate, and vitamin D in celiac patients [10,11]. Although the attention of the scientific community in the past years has been focused towards DF incorporation into bakery products, fiber deficiency in the diet, especially the GF diet, is still present globally.

Considering this background, optimization of GF formulations with fibers as nutritional and functional ingredients was intensively investigated, with the aspiration of making this branch of the bakery industry more competitive in the growing global GF market. Since the term DF includes diverse ingredients of plant origin, the most commonly used fiber sources for GF bread enrichment were GF cereal flours and brans, pseudocereal flours, seed flours (chia, chestnut), and isolated commercial fibers (inulin, fructooligosaccharides, β -glucan) [12,13]. Over the last decade, in line with sustainable development goals, fibers from the byproducts of the milling and fruit and vegetable processing industries have arisen as emerging sustainable ingredients in the production of fiber-enriched GF bread [14–19]. Conducted studies revealed that, besides enhanced nutritional value, added DF can improve GF batter’s strength, consistency, and viscosity, as well as volume, crumb texture, and sensory attributes, and prolong GF bread’s shelf-life [20,21], owing to their water-binding capacity, gel-forming ability, fat mimetic, and textural and thickening effects [22]. Corresponding physico-chemical properties of DF are also associated with positive physiological effects, such as cholesterol and fat binding, decrease in blood glucose levels, preventing constipation, and facilitating good colonic health [23], contributing to overall health improvement [24].

Although several previous reviews discussed the use of DF from diverse sources and their influence on GF bread production and quality [13–15], there is still a gap in revealing the link between DF functionality in GF batter with technological, sensory, and nutritional GF bread quality, especially from the viewpoint of insoluble and soluble DF (IDF and SDF, respectively). In this context, this review aspires to provide some insights on the role of IDF and SDF in changing GF batter’s fundamental rheological properties (flow and viscoelastic behavior) and on the reflection of these changes on GF bread’s technological quality (crust and crumb color, volume, crumb texture), moving then towards the assessment of fiber-enriched GF bread’s sensory and nutritional characteristics. DF sources encompassed within this review include GF cereal flours and brans, isolated commercial fibers (inulin, fructooligosaccharides, β -glucan), resistant starch, and byproducts of the fruit and vegetable processing industries.

The literature search was conducted in the Web of Science and Scopus databases, as well as in the Google Scholar search engine, with an aim to conduct an extensive reexamination of research and review articles regarding fiber-enriched GF bread production. The search terms used were “gluten-free”, “gluten-free bread” AND “dietary fiber”, “insoluble fiber”, “soluble fiber” AND “rheology”, “bread quality”, and “sensory evaluation”, including articles published from the year 2000 and concluding with 2021. The required criteria for article inclusion in this review were: (1) review and research studies dealing with analyzing DF sources for GF bread enrichment, and optimization of fiber-enriched GF bread formulations, respectively; (2) studies addressing fundamental rheological, technological,

sensory, and nutritional aspects of fiber-enriched GF bread; and (3) studies including GF cereal flours and brans, isolated commercial fibers, and byproducts of the fruit and vegetable processing industries as fiber sources for GF bread production. Studies examining the hydrocolloids, pseudocereal flours, and other alternative flours as DF sources for GF bread production were excluded.

2. Definition, Classification and Sources of Dietary Fibers Used in Gluten-Free Bread Production

DF are a large and heterogeneous group of compounds that include polysaccharides, oligosaccharides, and accompanying plant components [21]. Twenty years of debating were necessary to establish a consensus on a unique DF definition commonly recognized by all leading organizations dealing with food. During this period, proposed definitions underwent several revisions in order to reflect the chemical composition of DF, as well as their associated health benefits [25]. The universally accepted DF definition by the World Health Organization and Codex Alimentarius was adopted in 2009 and defines DF as “carbohydrate polymers with ten or more monomeric units that are not hydrolyzed by endogenous enzymes in human small intestine” [24–26]. The corresponding definition includes carbohydrate polymers (i) naturally occurring in food, (ii) obtained from raw food materials by a chemical, physical, or extraction process, or (iii) synthetic carbohydrate polymers where (ii) and (iii) include only those carbohydrates with a scientifically proven positive physiological impact on health [27]. It is precisely this demand which raises a question regarding the change in the initial number of monomeric units (degree of polymerization, DP) of the carbohydrate polymers stated in the adopted definition (DP10) and its reduction to three monomeric units (DP3) [27,28]. Regional authorities (the European Food Safety Authority, EFSA and the US Food and Drug Administration, FDA) took advantage of the flexibility allowed on this issue and revised the DF definition to include polysaccharides with three or more monomeric units, hence expanding the number of compounds regarded as DF [25]. Another question arising from the adopted definition is the impossibility of classifying lignin into the above carbohydrate polymers groups, despite its potential in having a physiological impact [27]. Thus, the mentioned drawbacks should be considered until the initial definition update, which is still pending.

Based on criteria such as water solubility, viscosity, microbiological fermentation in the colon, and the ability to stimulate the growth of certain bacteria, the common classification of DF includes [29–31] (pp. 39–68):

- Soluble dietary fiber (SDF), which includes non-cellulosic polysaccharides, oligosaccharides, and hydrocolloids such as pectin, β -glucan, and gums;
- Insoluble dietary fiber (IDF), which includes cellulose, hemicellulose, lignin, resistant starch, and products of Maillard reactions;
- Prebiotic dietary fiber, which includes inulin, inulin-type fructans, trans-galactooligosaccharides, and fructooligosaccharides.

Additional information on DF as prebiotics was recently reviewed and discussed by Rezende et al. [32].

From an analytical point of view, total dietary fiber (TDF) is referred to as the sum of SDF and IDF, which is further classified into low-molecular-weight dietary fiber (LMWDF) and high-molecular-weight dietary fiber (HMWDF) [28,33].

Structural diversity present among DF is the leading factor affecting DF properties such as solubility/insolubility and hydration, which further reflect on DF viscosity and fermentability [25]. Water holding, water binding, and swelling are commonly determined DF hydration properties that affect the rheological and physiological behaviors of DF and are primarily associated with, but not limited to, SDF [34]. Changes in the soluble/insoluble DF ratio and, consequently, in DF hydration properties can be achieved through various chemically or physically induced modifications acting on fiber structure and on parameters, such as particle size, porosity, specific surface area, and others [16,35–37]. An increase in viscosity and affinity towards gel formation are related to SDF, with further physiological

functions including reduced gastric emptying and slowing nutrient absorption [27]. On the other hand, IDF also exhibits certain hydration properties that are associated with the fecal bulking effect, due to limited digestion by the gut microbiota [34,38]. Familiarity with the mentioned hydration properties provides insight into the technological functionality of DF regarding fibers' application in food [39]. Enhanced nutritional value, sensory appeal, and, likewise, texture and shelf life of the product are the main reasons for DF enrichment, alongside physiological effects leading to proven health benefits [14,34]. Established DF physiological effects, such as cholesterol lowering, glycemic response reduction, and increased gut transit time, are recognized as preventive, and represent one of the main strategies for combating the development of emerging chronic noncommunicable diseases (CNCD) (coronary heart diseases, type 2 diabetes, obesity, colorectal cancer) [23–25,34].

As an intrinsic plant component, DF can be naturally found in a variety of sources, such as whole grains, fruits, vegetables, legumes, nuts and seeds, and subsequently isolated in a purified form regarded as functional fiber [40], which is commercially available. Additionally, food industry byproducts (peels, pulps, cores) have been frequently used and marked as sustainable DF sources [40,41]. Brans from different grains, apple and citrus pomaces [42], sugar beet pulp [43], and sugar cane bagasse [44] are the most commonly utilized byproducts as sources of DF for direct application, as well as for fiber isolation. An additional benefit of the byproducts application as sources of DF is the presence of associated bioactive compounds. In order to address the specific need, isolated DF can be further tailored by appropriate physical (thermal processing, micronization) or chemical (alkaline hydrogen peroxide treatment, carboxymethylation), as well as enzymatic modification methods to acquire the desired physico-chemical and functional properties [15,45–47]. Regarding GF products' enhancement with DF, pseudocereals (amaranth, quinoa, and buckwheat), wholegrain GF cereal flours and brans (oat), fruit and vegetable fibers and byproducts (defatted blackcurrant and strawberry seed flours, sugar beet fibers, apple, orange, pear, and pepper and tomato pomace), seed fibers (carob, chia, acorn, and chestnut), and isolated commercial fibers (cereal fibers, inulin, β -glucan, bamboo, and potato and pea fibers) [13,15,16,48] were until now included in GF formulations. Studies exploring fiber-enriched GF bread formulations are summarized in Table 1, alongside DF source and applied amount.

Table 1. Summary of studies exploring dietary fiber application in gluten-free bread formulations, including source and addition level.

Source	Addition Level (g/100 g)	Reference	Source	Addition Level (g/100 g)	Reference
Wholegrain cereal flours and brans			Resistant starch	10, 15, 20	[48]
				5, 10, 15	[49]
				5, 10	[50]
				7	[51]
Defatted rice bran	10	[22]	Isolated commercial fibers		
Rice bran	5, 20	[52]	Bamboo	10	[20]
Wheat bran	7	[51]	Potato	0.5, 1, 2	[53]
Millet bran	10	[54]	Pea	10	[20]
Teff	50, 70, 100	[55]	Rice bran	10	[22]
Pseudocereals			Oat bran	5, 10	[50]
Amaranth	50	[56]		1, 2	[57,58]
Buckwheat	50	[56]	β -glucan	5.6	[59]
	40	[60,61]		0.1–3.9	[62,63]
Quinoa	50	[56]		0.5, 1, 2	[64]
	40–100	[65]		1.8–11.8	[66]
	12.5–50	[67]		1.3, 2.6, 3.9	[68]

Table 1. Cont.

Source	Addition Level (g/100 g)	Reference	Source	Addition Level (g/100 g)	Reference
Fruit and vegetable byproducts			Cereal (oat, wheat, maize, barley fibers)	3, 6, 9	[21]
Green plantain	30	[69]	Nutriose®	10	[20]
Defatted blackcurrant seed flour	5, 10, 15	[70]	Polydextrose	10	[20]
Strawberry seed flour	5, 10, 15	[70]	Sugar beet fiber	0.5, 1.5	[71]
Apple pomace	5–20 2.5, 5, 7.5	[19] [73]	Citrus fibers	5.4–6.8 10, 15, 20	[72] [74]
Orange pomace	2, 4, 8 2.5, 5, 7.5	[18] [73]	Apple fibers	3, 5, 7	[17]
Prickly pear peel	2.5, 5, 7.5	[73]	Fibrillated cellulose	2, 4	[75]
Prickly pear seed peel	2.5, 5, 7.5	[73]	Cellulose	10 8, 10, 16, 18, 20	[20] [75]
Tomato pomace	2.5, 5, 7.5	[73]	Prebiotic dietary fibers		
Pepper pomace	2.5, 5, 7.5	[73]	Fructooligosaccharides	3, 5, 8	[76]
Sugar beet pulp	3, 5, 7	[16,17]	Inulin-type fructans	8.6, 17.9, 22.7, 28	[77]
Seed fibers				3, 5, 8	[76]
Acorn	20, 40, 60 5, 15, 25	[78] [79]		9	[59]
Chia seed and flour	15 10	[81] [83]	Inulin	4, 8, 12	[80]
				4, 8, 12	[82]
				5, 10	[50]
Chestnut	10–50, 100	[84–86]		10	[87]
				7.5	[51]

3. Role of Dietary Fibers in Gluten-Free Batter Rheology

The connection between applied stress and material response to this stress (flow or deformation) is described by rheological properties [88] (pp. 45–60). Investigation of bread dough's rheological properties is vital, considering its complex structure and the significant changes occurring in each technological process when different exposure times to deformation and the deformation intensity are applied [89,90]. Furthermore, information regarding bread dough's rheological properties is crucial in determining ingredient functionality during new product development, since they are linked to the dough's gas-holding capacity, baking performance, and the end product's quality [91].

Methods for determining bread dough's rheological properties can be divided into two categories [92] (pp. 209–257) [93]: empirical or descriptive methods and fundamental or basic methods. These methods are based on similar principles involving the monitoring of the dough response to the applied stress in different phases of the technological process. Although empirical methods are well established for wheat doughs, alternative empirical methods for GF batter are still developing [94]. The main disadvantages of empirical methods are: the application of inadequate and large deformation forces, and the impossibility of defining their intensity; expression of results in arbitrary units not included in the SI system and, therefore, the inability to calculate basic rheological parameters (stress, degree of deformation, and viscosity) or to provide constitutive equations; large sample volumes [91,95]; as well as the need for a detailed description of the experimental procedure to allow repeatability [96] (pp. 297–334). By applying fundamental rheological methods, it is possible to define and express the intensity of applied force, as well as basic rheological parameters (stress, deformation, viscosity), in absolute physical units. This enables the description of the dough's rheological behavior by mathematical equations corresponding to mechanical models and comparison of the results obtained on different rheometers. In addition, fundamental measurements are performed on small sample quantities [96]

(pp. 297–334) [97] (pp. 117–146). The influence of diverse ingredients in GF formulations, including DF, accompanied with different GF batter hydration levels, introduces difficulties in determining their effect on rheology [7]. Bearing this in mind, when studying the rheological properties of fiber-enriched GF batter samples, empirical rheological methods are rarely used, while the most commonly used fundamental methods include flow tests under steady-shear conditions, dynamic oscillatory frequency sweep tests, and creep–recovery tests, as discussed in more detail in the following sections.

Rheological analysis of GF batter samples enriched with fibers is commonly performed by excluding yeast from the formulation to avoid interference related to bubble formation and to diminish the heterogeneous nature of the sample for accomplishing stable readings [96] (pp. 297–334). Rheometers with parallel plate geometry are frequently used in rheological measurements of GF batter. Depending on the consistency of the fiber-enriched GF batter and the applied stress used, plates have a diameter ranging from 20 to 60 mm and a flat or serrated surface [66,72,80]. After placing the sample, the gap between the plates is usually adjusted from 1 up to 4.5 mm [73,80], whereby the excess sample is carefully removed and the edges of the plates are covered with oil to prevent the sample from drying out [96] (pp. 297–334). In order to diminish the residual stress, GF batter is relaxed for 10 to 20 min after mixing [17], and is then placed on the rheometer’s sensory plate where it rests for another 3 to 15 min before starting the measurement [16,80]. Comparing rheological properties between diverse fiber-enriched GF formulations brings difficulties in differentiating the fiber impact on fundamental rheological parameters, considering the added fiber’s origin, purity, molecular weight, variations in the formulation’s composition, and hydration level. However, the following sections are intended to provide overall principles on the action of an added fiber on a GF batter’s structure, although it should be stated that the mentioned fiber effects are not ambiguous.

3.1. Effect of Dietary Fibers on Gluten-Free Batter Flow Properties

Considering that GF dough is frequently referred to as batter, it adapts well to a flow test enabling determination of the ingredients’ effect on its ability to flow. In general, the flow properties of fiber-enriched GF batter formulations are determined under steady-shear conditions by applying a shear-rate range from 1 to 100–200 s^{−1} [17,21,85]. The fiber-enriched GF system is acted upon by a constant stress/strain rate over time, and the resulting stress/strain rate is measured and described with a general equation (model) [96] (pp. 297–334). The Ostwald–de Waele or power law model (Equation (1)) is successfully used to adequately describe the experimental data and to establish the flow properties of fiber-enriched GF batter [17,21,73,74,80]:

$$\tau = K \times \gamma^n, \quad (1)$$

where τ represents shear stress (Pa), K is the consistency index (Pa sⁿ), γ is the shear rate (s^{−1}), and n is the flow behavior index (dimensionless). From the power law model, the apparent viscosity η_{ap} of fiber-enriched GF batter samples can be also calculated using Equation (2):

$$\eta_{ap} = K \times \gamma^{n-1}, \quad (2)$$

Flow-behavior index values of fiber-enriched GF batter formulations investigated to date ranged from 0.249 to 0.264 for citrus fiber addition [74], from 0.276 to 0.328 for addition of inulin [80], from 0.591 to 0.726 for GF batter enriched with wheat, maize, oat, and barley fibers [21], and from 0.67 to 0.99 for added sugar beet and apple fibers [17]. However, some extremes are also reported in GF formulations including byproducts, such as dried orange pomace, dried apple pomace, dried tomato peel, dried prickly pear peel, and dried prickly pear seed peel, where negative values of the flow behavior index were observed [73]. Reported flow-behavior index values <1 confirmed the shear-thinning (pseudoplastic) behavior of fiber-enriched GF batter formulations, elucidated by microstructure alignment towards the flow direction with an increase in the shear rate, leading to a decrease in

apparent viscosity [98]. A decline in the flow behavior index was observed in GF batter formulations with citrus fiber content of 10–20 g/100 g [74] and 2.5–7.5 g/100 g of fibers from byproducts (orange and apple pomace, and tomato and pear peel) [73] compared to the control, indicating their greater susceptibility to shear stress when high-range deformations are applied. In both studies, the GF batter's hydration levels were adjusted according to the added fiber's requirements and a fixed amount of hydrocolloid was used. Conversely, the addition of maize, oat, barley, sugar beet, and apple fibers, considered as predominantly IDF, resulted in higher values of the GF batter's flow behavior index at properly adjusted hydration levels [17,21]. The presence of insoluble matter and the formation of networks composed of hydrated cellulose and hemicellulose were considered responsible for this enhancement in GF batter viscosities [21]. Nevertheless, an increase in sugar beet and apple fiber content from 3 to 7 g/100 g reduced the GF batter's flow-behavior index value when the amount of hydrocolloid in the GF system was lower, indicating an amplified, coupled influence of ingredients with high water affinity beyond the fiber's individual effect [17]. Furthermore, regarding SDF inclusion, the addition of 4–12 g/100 g inulin with low and medium degrees of polymerization ($DP < 10$, $DP \geq 10$, $DP > 23$) also led to an increase in the GF batter's flow behavior index, although an increase in inulin $DP < 10$ and $DP \geq 10$ content required a reduction of the hydration level, while an increase in inulin $DP > 23$ content required a higher hydration level than the control [80].

As regards to the consistency index values, compared to the control, a decline was reported with increasing fiber content, ranging from 187 to 296.3 Pa sⁿ in GF batter formulations with 4–12 g/100 g inulin [80], from 391.3 to 428 Pa sⁿ for citrus fiber at 10–20 g/100 g addition [74], and from 103 to 1045 Pa sⁿ when byproducts with fibers at 2.5–7.5 g/100 g were included [73]. This decline in consistency index values could be linked to limited water availability for other GF batter constituents when a hygroscopic fiber, such as inulin, is included in the formulation [80], or to the conducted pre-hydration of the fiber rich byproducts (orange and apple pomace, tomato and pear peel) before incorporation into the GF batter [73]. Additionally, GF batter formulations with predominantly SDF (polydextrose, Nutriose[®], and inulin with low and medium DP) demanded reduction of previously adapted GF batter hydration levels to achieve consistencies similar to the control [96] (297–334) [20,80]. Juszczak et al. [80] also revealed that, above a certain level of inulin addition, no further change in the GF batter's consistency occurred. However, the addition of wheat, maize, oat, barley, sugar beet, and apple fibers to the GF batter formulation reflected an increase in consistency index values, which were in the range of 1.2–33.6 for sugar beet and apple fibers at 3–7 g/100 g addition [17], and 3.3–4.7 with the inclusion of wheat, maize, oat, and barley fibers at 3–9 g/100 g [21]. It is supposed that the increase in the consistency index, as well as in the GF batter's viscosity, resulted from the entanglement of optimally hydrated cellulose and hemicellulose chains originating from the added predominantly insoluble fibers, leading to the creation of additional resistance to flow [17]. Likewise, for regular dough, GF batter's consistency is an important physical characteristic influencing the end product's quality (loaf volume), considering its role in retention of the small air bubbles initially incorporated into the dough during mixing [99]. Air bubbles entrapped in the dough can rise and persist in bread throughout the baking stage when the apparent viscosity of the dough is high, reflecting a high loaf volume and porosity values, as reported for GF bread with maize and oat fibers. Conversely, low apparent viscosity values led to a lower GF bread loaf volume when wheat fiber was added, establishing a positive correlation among these parameters [21]. Although the addition of SDF (inulin with low and medium DP) reduced the GF batter's consistency index values [80], while the added IDF mainly expressed the opposite effect on the GF batter's apparent viscosity [21], in both cases, enhanced GF bread loaf volume is achieved. This fact could be explained by differences in the initial consistency index values for the control GF batter found by Juszczak et al. [80], which was 347 Pa sⁿ compared to the very low value of 3.58 Pa sⁿ reported by Sabanis et al. [21]. The presented results indicate the existence of an optimal

GF batter consistency for reaching a satisfying GF bread loaf volume, and the contribution of added fibers to the accomplishment of this goal [96] (pp. 297–334).

In general, the influence of added fiber on the GF batter's flow properties was predominantly associated with fiber type (insoluble/soluble) and quantity, as well as with the GF batter's hydration level, presence, and variations in other GF batter constituents (hydrocolloids) [96] (pp. 297–334).

3.2. Effect of Dietary Fibers on Gluten-Free Batter Viscoelastic Behavior

While the determination of flow properties provides information on the GF batter's rheological characteristics regarded as fluid, oscillatory tests and creep–recovery tests enable the assessment of both viscous and elastic GF batter components and, accordingly, their viscoelastic behavior [96] (pp. 297–334).

3.2.1. Dynamic Oscillatory Frequency Sweep Tests in Fiber-Enriched Gluten-Free Batter Formulations

The principle of dynamic oscillatory measurements is based on the subjection of the examined viscoelastic system to sinusoidal oscillatory stress/deformation in a certain time period, and recording the system's response to the applied deformation in the form of sinusoidal stress [88] (pp. 45–60) [100] (pp. 159–213). Furthermore, oscillatory measurements enable characterization of different GF batter formulations without structural damage [96] (pp. 297–334). Frequency sweep oscillatory measurements are frequently used to indicate changes in the properties of the elastic and viscous components of fiber-enriched GF batter formulations with an increase in frequency [16,20,48,66,68]. The mechanical spectra of fiber-enriched GF batter formulations, depicting the elastic (storage) G' and viscous (loss) G'' modulus versus frequency, are determined under constant stress in the linear viscoelastic region (LVR) by applying a range of frequencies between 0.05 and 100 Hz [19,20]. Another parameter describing the contribution of viscous and elastic components to overall viscoelastic behavior of fiber-enriched GF batter formulations is the loss tangent ($\tan \delta$) and it is calculated using Equation (3):

$$\tan \delta = G''/G', \quad (3)$$

where $\tan \delta$ represents the loss tangent, G' is the elastic modulus (Pa), and G'' is the viscous modulus (Pa). Additionally, $\tan \delta$ indicates the level of structural organization (molecular interactions) within the system, and hence, highly structured systems express low $\tan \delta$ values [101].

The dependence of G' and G'' modulus on angular frequency typically follows a linear evolution in the double logarithm scale, especially in the range of 1–10 Hz, enabling fitting of the experimental data to equations (likewise called power law) [48,64,66,68,74,80]:

$$G'(\omega) = G'_{\omega 1} \times \omega^a, \quad (4)$$

$$G''(\omega) = G''_{\omega 1} \times \omega^b, \quad (5)$$

$$\tan \delta(\omega) = G''(\omega)/G'(\omega) = (G''/G')_{\omega} \times \omega^c = (\tan \delta)_{\omega 1} \times \omega^c, \quad (6)$$

where coefficients $G'_{\omega 1}$, $G''_{\omega 1}$, and $(\tan \delta)_{\omega 1}$ represent the elastic and viscous modulus and the loss tangent at a frequency of 1 Hz. Exponents a , b , and c define the degree of modulus and loss tangent dependence with oscillation frequency [96] (pp. 297–334).

The application of small deformations that do not correspond to real deformations to which the GF batter is exposed during mixing and fermentation is considered as the main drawback of dynamic oscillatory tests. However, the action of small deformations induces reversible changes in the GF batter's structure, providing information regarding molecular interactions in this unaltered system [101]. This enables the studying of the influence of water's and other ingredients' (fibers, hydrocolloids) actions on the GF batter's properties [102] (pp. 52–82) [95], which is especially important considering that the dynamic

parameters of networked hydrated structures are very sensitive to the ingredient type and concentration, as well as the water amount [103].

In general, the frequency sweep test performed in LVR shows that, in a GF batter formulation enriched with inulin, citrus fibers, resistant starch, β -glucan, and cellulose fibers [48,64,66,68,72,74,75,80], the elastic modulus (G') was higher than the viscous modulus (G'') in the entire frequency range, with $\tan \delta < 1$, indicating the prevalence of elastic over viscous properties. Additionally, the resulting G' and G'' dependence on the angular frequency and reported $\tan \delta$ values ranging from 0.25 to 0.65 imply that fiber-enriched GF batter formulations manifested rheological properties typical for weak gels [48,64,68,74,75,80]. Increasing the amounts of predominantly IDF, such as citrus fiber (10–20 g/100 g) [74], resistant starch (10–20 g/100 g) [48], and insoluble yeast and fungi (1–3) (1–6)- β -glucan (0.5–1 g/100 g) [64], led to an increase in G' and G'' modulus of fiber-enriched GF batter formulations. Moreover, a decline in $\tan \delta$ values was recorded for the corresponding fiber-enriched GF batter formulations, denoting structure strengthening. Conversely, decreases in G' and G'' modulus were observed with a rising amount of predominantly SDF as inulin (4–12 g/100 g), with low/medium DP ($DP < 10$, $DP \geq 10$) [80] and soluble yeast (1–3) (1–6)- β -glucan (0.5–1 g/100 g) [64] reflecting in higher $\tan \delta$ values and, hence, shifting toward viscous properties for GF batter formulations with low DP inulin [80], while $\tan \delta$ remained unaltered upon soluble yeast β -glucan inclusion [64]. In addition, similar behavior regarding IDF and SDF action on G' and G'' modulus and $\tan \delta$ was confirmed when 10 g/100 g of insoluble cellulose, potato and pea fiber, and soluble polydextrose and Nutriose[®] fibers were included in the GF batter [20]. An exception is observed with the inclusion of low, medium, and high-molecular-weight oat and barley (1–3) (1–4)- β -glucan (1.3–11.8%), since these SDF exerted the same influence on G' and G'' modulus and $\tan \delta$ as IDF [66,68].

This opposite influence of IDF and SDF on G' and G'' modulus, $\tan \delta$, and overall GF batter viscoelastic behavior is presumably attributed to intrinsic changes in the GF batter's structure induced by fiber addition (Figure 1).

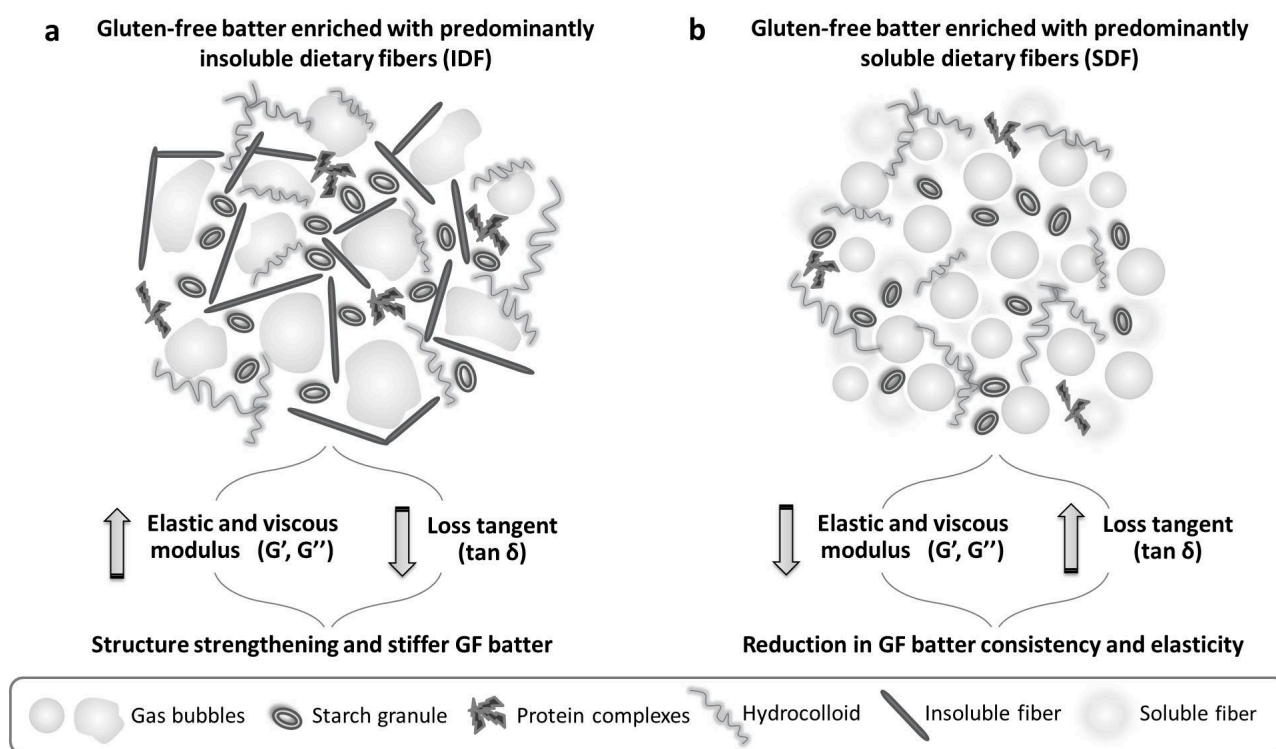


Figure 1. Microstructure of gluten-free batters enriched with (a) predominantly insoluble and (b) soluble dietary fiber.

Accordingly, greater and more irregular GF batter structures were established upon IDF addition. This effect is elucidated by IDF shape regularity [64] and slight changes in shape (fiber rounding) occurring in the presence of starch granules [20] (Figure 1a). A greater impact on the GF batter's structure exhibit larger and rounder IDF [20]. Additionally, it is assumed that both IDF and flour particles act as rigid fillers in spite of the shape differences. The IDF rigidity is more pronounced compared to hydrated flour particles, but a further increase in the flour particle's rigidity is a consequence of the competition for the available water between IDF and starch, resulting in the GF batter's structure strengthening upon IDF inclusion [75]. However, the corresponding influence of IDF on the GF batter's consistency and elasticity is not always positive, since firmer GF batters require additional water level adjustments [20,21]. Furthermore, the creation of such irregular and disrupted GF batter structure brings difficulties in air incorporation during mixing and further retention and uniform distribution of the air bubbles [20]. Dissolving of SDF in the aqueous solution, alongside other soluble GF batter constituents (hydrocolloids), enables the envelopment of starch granules and lubricates the GF batter, limiting the available starch granules for water adsorption, which manifests as a reduction in the GF batter's consistency and elasticity [20] (Figure 1b). Although in some cases, the reduction in water levels is required upon SDF incorporation [80], GF batters still exhibit uniform internal structure, which enables greater incorporation of air as smaller bubbles into the GF batter, as compared to IDF [20].

These are the general observations concerning IDF and SDF influence on the GF batter's G' and G'' modulus and $\tan \delta$, but many exceptions can appear when considering the involvement of diverse fibers and other ingredients in different quantities in a complex GF formulation. Theoretically, several different regions describing the behavior of the fiber-enriched GF batter system in the scope of the applied frequencies can be observed: a viscous or terminal region in which $G'' > G'$ and the viscous behavior dominates; the transition region in which the G'' and G' values are equalized, leading to their intersection on the so-called crossover frequency; with a further increase in the G' value after the crossover point improvement in the elastic properties of the system occurs; and in the rubbery/plateau region, the elastic behavior dominates ($G' > G''$) [104]. As discussed above, in most of the fiber-enriched GF batter formulations, elastic behavior dominates over viscous ($G' > G''$). However, the occurrence of crossover points is recorded in GF batter samples with 17.8 and 20 g/100 g of apple pomace, and 3–7 g/100 g sugar beet fiber [16,19]. In both studies, crossovers were observed at lower or higher frequencies depending on fibers concentration, water amount, and possible interactions with hydrocolloid present in the GF batter system [16,19]. Crossover appearance at lower frequencies indicates a faster transition of fiber-enriched GF batter from viscous to elastic behavior when fiber concentration increases [19], and in the presence of appropriate water levels, which allow adequate dispersion of fibers and hydrocolloid, and expression of their hydration properties leading to sustainable GF structure formation [16]. In addition, domination of G'' over G' and the expression of predominantly viscous behavior with $\tan \delta > 1$ was reported for GF batters enriched with sugar beet fibers. This behavior was ascribed to the presence of free water in the system, leading to dilution of the constituents' effects [16,62], since with the water level increase, the value of $\tan \delta$ rose concurrently [57].

It can be observed that the fiber quantity and type can affect the GF batter's G' and G'' modulus, $\tan \delta$, and overall viscoelastic behavior. However, the extent of the corresponding fiber influence is certainly dependent on available water and on excess or lack of other structural ingredients, although the fiber's molecular weight and DP also strengthen or diminish the fiber-enriched GF batter's structure.

3.2.2. Creep–Recovery Tests in Fiber-Enriched Gluten-Free Batter Formulations

In addition to the application of oscillatory stress, the viscoelastic properties of fiber-enriched GF batter formulations can be also defined by applying constant stress over a period of time, namely, conducting the creep and recovery test. The creep and recovery

phenomenon is linked with the reorientation of bounds established within the viscoelastic system [105]. The principle of the creep and recovery test relies on the application of constant stress and on monitoring the evolution of strain with time (creep phase), and subsequently recording the deformation reduction after stress removal (recovery phase) [96] (pp. 297–334). Creep and recovery tests have found wide application in the examination of fiber-enriched GF batter's viscoelastic properties, predominantly within the LVR, with applied constant stress ranging from 0.1 to 8 Pa [16,66], the creep phase lasting 60 or 150 s, and an allowed recovery phase duration of 180 or 300 s [48,68]. The recovery phase duration is typically two times longer compared to the creep phase, allowing the system to reach an equilibrium state [100]. Elastic or viscous deformations that occur in the fiber-enriched GF batter at a constant stress can be characterized in terms of compliance (J), and are commonly mathematically described using the four-element Burgers model, comprising the association in series of the Maxwell model and the Kelvin–Voigt model. The Burgers model is represented by Equation (7) for the creep phase and (8) for the recovery phase [96] (pp. 297–334) [16,48,64,66,68,74,80]:

$$J(t) = J_0 + J_1 [1 - \exp(-t/\lambda)] + t/\eta_0, \quad (7)$$

$$J(t) = J_{\max} - J_0 - J_1[1 - \exp(-t/\lambda)], \quad (8)$$

where J_0 (1/Pa) represents the instantaneous compliance, J_1 (1/Pa) is the retarded elastic compliance or viscoelastic compliance, J_{\max} (1/Pa) is the maximum creep compliance, λ (s) is mean retardation time, and η_0 (Pa s) is zero shear viscosity.

Additionally, the fiber-enriched GF batter's recovery value (R) can be calculated using Equation (9) [74]:

$$R(\%) = (J_0 \times J_1/J_{\max}) \times 100, \quad (9)$$

A reduction in the GF batter's J_0 , J_1 , and J_{\max} was reported after incorporation of predominantly IDF, such as citrus fiber, resistant starch, insoluble yeast, and fungi (1-3) (1-6)- β -glucan [48,64,74]. A decrease in creep and recovery compliances was further amplified by increasing the aforementioned IDF amounts, indicating reduced GF batter susceptibility to the applied constant stress. When GF batter was enriched with sugar beet fibers, a slight decline in compliances was also observed [16]. Reductions in creep and recovery compliances were reflected in increased steady state viscosity values of GF batters enriched with IDF [16,48,64,74]. Additionally, a greater GF batter recovery upon stress release was reported after inclusion of citrus fibers [74]. A positive IDF effect on GF batter creep and recovery parameters could be associated with high water affinity and the retention capacity of these fibers [64,74,106]. The obtained low creep and recovery compliances and high steady state viscosity values for GF batter enriched with IDF are in accordance with the increased G' and G'' modulus and low $\tan \delta$ values observed by the oscillatory testing (Figure 1a) [48,64,74].

Inclusion of predominantly SDF as inulin with low/medium DP ($DP < 10$, $DP \geq 10$, $DP > 23$) raised the values of the GF batter's J_0 and J_1 , showing susceptibility to deformation, with this effect further magnified by their rising amounts (4–12 g/100 g) [80]. However, in the case of inulin with $DP > 23$, an exception was denoted at the addition of 12 g/100 g, since a decline in compliances was observed, probably induced by the concurrent rise in water amount [80]. Inulin with a low DP expressed high solubility, resulting in the GF batter being more susceptible to stress, while reduced solubility of inulin with a higher DP limited water availability and enabled the strengthening of the GF batter's structure by amplifying the structure-forming action of the applied hydrocolloids [80]. The mentioned effect of different inulin types is also reflected in the GF batter's steady state viscosity, where an increase in inulin with a low DP induced a decline in the steady state viscosity, while increasing levels of inulin with a higher DP led to higher steady state viscosity values. It was confirmed that the impact of the inulin type on the GF batter's steady state viscosity was more pronounced compared to the inulin level [80]. The addition of soluble yeast (1-3) (1-6)- β -glucan had no effect on the GF batter's J_0 and steady state viscosity, but J_1 and J_{\max}

increased regardless of the fiber amount added (0.5–2 g/100 g) [64]. However, in the case of low-, medium-, and high-molecular-weight barley and oat (1-3) (1-4)- β -glucan, reduction in the GF batter's compliances and increased steady state viscosity were accomplished with increasing fiber levels alongside a concurrent water increase [66,68]. This acting of β -glucan as IDF, in spite of its soluble nature, is elucidated by its ability to form highly viscous (pseudoplastic) solutions [68]. The obtained results for creep and recovery parameters of GF batter enriched with SDF are in agreement with the lower G' and G'' modulus and higher or unaffected $\tan \delta$ values observed by the oscillatory testing upon addition of inulin and soluble yeast (1-3) (1-6)- β -glucan [64,80], and the higher G' and G'' modulus accompanied with low $\tan \delta$ values after barley and oat β -glucan inclusion [68]. Higher compliance values in GF batter enriched with SDF are not necessarily a drawback since, up to a certain limit, they generally allow better dough development in the proofing and baking stages [96] (pp. 297–334). Furthermore, a dilution of the GF batter system upon inulin addition promotes reorientation of the other structural elements, resulting in a higher recovery rate after applied deformation (Figure 1b) [80].

4. Role of Dietary Fibers in Gluten-Free Bread's Technological Quality

The appealing visual impression is the most common trigger for purchasing food products and the same applies to GF bread. However, GF bread's appearance is usually far from anticipated, demonstrating numerous defects in terms of technological quality, including pale crust and crumb color, reduced volume, undeveloped crumb structure, and crumbly texture compared to wheat counterparts [5–7]. The corresponding quality defects arise from the GF batter's inability to provide adequate gas expansion and retention during proofing, leading to reduced GF bread volume and crumb softness [107]. Alongside hydrocolloids, proteins, and enzymes, DF are one more functional ingredient investigated to address these GF bread quality defects caused by gluten absence. Commonly assessed indicators of fiber-enriched GF bread technological quality are crust and crumb color, specific volume, and crumb texture parameters, such as hardness, cohesiveness, chewiness, springiness, and resilience, as discussed in more detail in the following sections. Fiber-enriched GF bread technological quality was usually estimated 1, 2, or 24 h after baking [20,50,72].

4.1. Effect of Dietary Fibers on Gluten-Free Bread Crust and Crumb Color

Since color represents one of the determining factors for consumers' acceptability, perceiving an appealing color will enhance GF bread's acceptance. The typically pale color of GF bread originating from a high share of ingredients such as starch and refined flour can be perceived as repulsive, and DF addition is recognized as an effective way of overcoming the corresponding drawback [20,22,52,54]. DF addition in GF bread formulations evinces a double effect on the final product's color, as a consequence of promoting Maillard and caramelization reactions, and of the natural coloration of DF. Crust color is related to the Maillard and caramelization reactions' occurrence during baking, in which reducing sugars from SDF susceptible to partial hydrolysis participate as precursors [20]. Conversely, IDF inclusion introduces minimal crust color changes without interfering with the corresponding reactions [20,21]. Crumb color is mainly affected by the initial color of DF and of the other ingredients used because lower temperatures disable the mentioned reactions' occurrence [17,21,58]. Apart from DF addition, the formulation's physico-chemical properties (water content, hydrocolloids, reducing sugars and amino acid content, pH), as well as baking conditions (temperature, relative humidity, modes of heat transfer) also affect the product in terms of color [17,21,63,108]. High water content in formulations is usually linked to pale crust color due to dilution of reducing sugars and amino acids, reflecting a decreasing rate of the Maillard reactions [17,21,63].

The colors of the crust and the crumb are commonly expressed in the CIELab color space, a mathematical model encompassing the range of human color perception through basic parameters L^* (lightness), a^* (redness), and b^* (yellowness). In addition, crust and crumb parameters such as chroma (C^* , purity of the color) and hue (h), as well as the

whiteness index (WI) of the crumb and the browning index (BI) of the crust can be obtained through calculations [17,52,63]. Nevertheless, L^* is regarded as the foremost parameter for GF bread's crust and crumb color representation [58].

Introduction of predominantly IDF from various sources in GF bread formulations resulted in darker crust, as well as crumb, colors. The addition of micronized millet, diverse rice bran types, and fibers from maize and barley were reflected in lower L^* values, indicating an increase in crust and crumb darkness, and reaching the desired appealing color [21,22,54]. Furthermore, β -glucan originating from spent brewer's yeast inclusion gave a darker crumb color [58], conversely to barley's β -glucan, which resulted in an increase in crust lightness [63]. Regarding fruit and vegetable as DF sources, apple pomace and fiber usage provided a darkening effect on the crust and especially the crumb, further amplified by the increase in applied amounts [17,19,73], which was mainly attributed to the fibers' original coloration. The same course of action on crust and crumb color was reported for the addition of dried orange pomace and dried prickly pear peel, as well as dried tomato and pepper peels [73]. Nevertheless, inclusion of modified sugar beet fibers in the GF formulation exhibited a tendency towards increased as well as decreased crust lightness, depending on the applied fiber and hydrocolloid amount. However, crumb color followed the trend of decreasing in lightness, regardless of the sugar beet fiber amount included [17]. While the application of predominantly IDF, namely bamboo, pea, and oat fibers, derived similar or higher crust lightness compared to the control GF bread, SDF use, namely Nutriose[®] polydextrose and inulin-type fructans, led to a significant decrease in crust lightness, attributed to the promoted generation of the precursors included in the Maillard reactions [20,77,109].

4.2. Effect of Dietary Fibers on Gluten-Free Bread's Specific Volume

GF bread's loaf volume is one of the paramount visual characteristics affecting consumers' choice and depends on several factors, including starch amylose and amylopectin content, batter viscosity, aggregation of the present protein upon heating, and presence of surface active compounds [110]. Commonly applied methods for the determination of fiber-enriched GF bread's loaf volume are rapeseed displacement, following the AACC method 10-05 [16,17,19,22,52–54,72,73,87,111], and by using a Volscan Profiler volume analyzer (Stable Micro Systems, Surrey, UK) [20,64,68,74]. As an indicator enabling quantitative measurements of baking performance, GF bread's specific volume is further calculated by dividing bread volume (cm^3) with bread weight (g) [52].

Reported GF bread specific volumes ranged from 1.14 to 4.45 cm^3/g for breads including predominantly IDF [52,64] and 2.04–5.09 cm^3/g when predominantly SDF were added (Table 2) [20,68]. Apart from fiber type (IDF or SDF), fiber-enriched GF bread's specific volume was also affected by the added fiber's extent and source, with some discrepancies in the obtained results.

Table 2. Specific volume and hardness values reported for gluten-free breads with predominantly insoluble and soluble dietary fibers.

Source	Addition Level (g/100 g)	Specific vol. (cm^3/g)	Hardness (N)	Reference
Predominantly insoluble fiber				
Millet bran	10	2.02–2.04	13.4–13.7	[54]
Rice bran	5, 20	1.14–1.58	0.26–0.68	[52]
	10	2.90–3.46	5.36–14.47	[22]
Oat bran	5, 10	2.42–2.70	1.58–2.10	[50]
Oat fiber	10	2.86–3.89	11.62–42.71	[20]
Potato fiber	0.5, 1, 2	2.5–2.9	/	[53]
	10	2.5	/	[20]
Pea fiber	10	2.77	29.80	[20]

Table 2. Cont.

Source	Addition Level (g/100 g)	Specific vol. (cm ³ /g)	Hardness (N)	Reference
Bamboo fiber	10	2.75–3.82	10.19–52.75	[20]
Resistant starch	5, 10	2.36–2.50	1.80–2.54	[50]
Insoluble β -glucan	0.5, 1, 2	3.77–4.43	0.37–0.55	[64]
Citrus fiber	5.4–6.8	2.56–3.43	/	[72]
Orange pomace	2.5, 5, 7.5	2.00–2.46	/	[73]
	2, 4, 8	2.3	1.34–8.60	[18]
Prickly pear peel	2.5, 5, 7.5	1.83–2.50	/	[73]
Prickly pear seed peel	2.5, 5, 7.5	1.72–2.02	/	[73]
Tomato pomace	2.5, 5, 7.5	2.10–2.21	/	[73]
Pepper pomace	2.5, 5, 7.5	1.69–2.10	/	[73]
Apple pomace	2.5, 5, 7.5	2.02–2.16	/	[73]
	5–20	1.6–3.2	0.93–4.15	[19]
Apple fiber	3, 5, 7	1.72–3.97	2.10–13.93	[17]
Sugar beet fiber	3, 5, 7	1.52–2.44	2.29–22.74	[17]
Predominantly soluble fiber				
Oat β -glucan	1.8–11.8	1.93–2.75	1.30–2.04	[66]
	1.3, 2.6, 3.9	2.04–3.17	1.21–6.53	[68]
Barley β -glucan	1.8–11.8	2.40–2.56	0.93–4.15	[66]
Yeast β -glucan	0.5, 1, 2	3.57–3.83	0.37–0.60	[64]
Inulin	10	2.28–2.69	1.34–2.62	[87]
Nutriose®	10	4.25	7.01	[20]
Polydextrose	10	5.09	5.18	[20]

The addition of predominantly IDF, such as cellulose, resistant starch, apple pomace, potato, citrus, wheat and pea fiber, and coarse bamboo and oat fibers, reduced the GF bread's specific volume, with the volume-depressing effect being more pronounced with increasing IDF amounts (Table 2) [19–21,48,50,53,74,75]. Conversely, the inclusion of rice and millet bran, citrus, apple, oat, barley, and maize fiber, fibers from byproducts (orange and apple pomace, tomato, and pear peel), fine bamboo and oat fibers, and insoluble yeast and fungi (1–3) (1–6)- β -glucan yielded GF bread with specific volumes higher than that of the control (Table 2) [17,20–22,52,54,64,72,73]. Furthermore, in the case of orange pomace and sugar beet fibers, the GF bread's specific volume raised concurrently with increasing fiber and water amounts up to a particular level, after which a volume-depressing effect was observed [17,18]. The negative influence of IDF on fiber-enriched GF bread's specific volume can be elucidated by fiber hydration properties and presence of water in the GF batter system. When the GF batter system disposes of limited water levels, the addition of an IDF possessing a high water affinity leads to the creation of a rigid and inflexible GF batter structure unable to rise [15,50]. On the other hand, increased water adsorption of the GF batter upon IDF addition requires further increase in water levels, which in many cases, leads to the dilution of structure-forming ingredients, production of uneven and unstable air bubbles (Figure 1a), and hence, a GF batter system incapable of retaining gas [17,18,81]. Additionally, coarse IDF can create points of rupture in a formed GF batter structure, allowing gas to escape and, therefore, diminishing the GF bread's specific volume (Figure 1a) [15,20]. A positive IDF effect on fiber-enriched GF bread's specific volume is mainly ascribed to interactions among IDF compounds and proteins present in the GF system, where fibers act as structure-building aids allowing better gas retention [20,21,52],

while some authors consider that the IDF-to-SDF ratio in predominantly IDF also contributes to their overall favorable influence on the GF bread's specific volume [15,22].

Overall, the inclusion of predominantly SDF, such as inulin, Nutriose[®], polydextrose, and β -glucan, yielded GF breads with high specific volumes (Table 2), although β -glucan inclusion showed some limitations [20,21,64,68,77,109]. Sciarini et al. [50] observed a concurrent increase in the GF bread's specific volume with increasing amounts of inulin; meanwhile, Morreale et al. [87] reported that GF bread's specific volume was nearly unaffected upon the addition of inulin with a different DP. The addition of β -glucan with different molecular weights derived from oat and barley up to 1.9 g/100 g and soluble yeast β -glucan up to 2 g/100 g had a positive influence on the GF bread's specific volume, while a further increase in the β -glucan amount (3.9 g/100 g) led to a volume-depressing effect [64,68]. Furthermore, Ronda et al. [66] revealed a decline in GF bread's specific volume upon oat and barley β -glucan inclusion at low GF batter hydration levels, and attributed this effect to water restriction and insufficient purity of β -glucan, due to the presence of maltodextrins [68].

Accordingly, the positive action of β -glucan on GF bread's specific volume is primarily attributed to its concentration, and afterward, to its molecular weight, adapted batter hydration levels, and purity [64,66,68]. High GF bread specific volumes obtained after SDF addition are generally related to SDF acting as aids in network formation, which envelope flour particles and starch, making the GF batter more cohesive and enabling expansion, uniform arrangement, and retention of gas bubbles (Figure 1b) [20].

As generally observed, higher specific volumes of fiber-enriched GF breads were attained from GF batters with lower consistency, whereas batters with higher consistency yielded GF breads with reduced volumes [20]. Attempts have been made to establish the relationship among fiber-enriched GF batter's fundamental rheological parameters and GF bread's specific volume. Greater specific volumes of GF breads enriched with both IDF and SDF are attained, even though IDF addition was accompanied by a higher consistency index and apparent viscosity values, whilst SDF inclusion induced the opposite effect. This effect was explained by different initial consistency values, as discussed in more detail in Section 3.1 [17,21]. A statistically significant negative correlation between GF bread's specific volume and G' , as well as a positive correlation with $\tan \delta$, were confirmed after β -glucan inclusion, denoting a concomitant increase in specific volume with a decrease in the GF batter's consistency and increase in $\tan \delta$, when working at adopted water levels [66,68]. The corresponding correlations, however, could not be relevant for all fiber-enriched GF batter formulations, when considering water amount as a variable with a great influence on $\tan \delta$ (as discussed in Section 3.2.1), as well as the IDF-to-SDF ratio in predominantly insoluble or soluble fibers, taking into account their potential influence on the GF bread's specific volume, discussed previously. Accordingly, the value of $\tan \delta$ alone cannot be a valid predictor of fiber-enriched GF bread's specific volume in terms of both IDF and SDF inclusion [15].

4.3. Effect of Dietary Fibers on Gluten-Free Bread's Crumb Texture

GF bread is characterized by greater crumb hardness and increased staling rates, compared to wheat counterparts. Evincing differences in crumb texture attributes between GF and wheat bread are primarily related to the high percentage of starch used in GF formulations and to gluten absence, where starch is prone to retrogradation due to the lack of interactions with proteins, resulting in GF breads undergoing fast staling [112]. A commonly employed method for estimation of fiber-enriched GF bread's textural properties is texture profile analysis (TPA) performed on a texture analyzer. During TPA, a GF bread slice is subjected to a double compression in a reciprocating motion that imitates the action of the jaw [113]. Texture analyzers used in the texture assessment of fiber-enriched GF bread were equipped with load cells of 5 and 30 kg [17,18,22,54,87], and cylinder probes with diameters ranging from 20 to 100 mm, [17,19,20,22,64] employing a percentage of compression from 20 to 50% [22,50,52,53,66], with a delay between the two compressions

of 5 or 30 s [17,20,66]. Frequently assessed indicators of fiber-enriched GF bread's textural properties include hardness, springiness, cohesiveness, chewiness, and resilience, which are calculated from the TPA graph.

GF bread's hardness represents a paramount textural parameter, considering its strong correlation with consumers' perception of bread freshness [112]. It is defined as the force required to attain a given deformation [113]. Hardness values for GF breads enriched with predominantly IDF ranged from 0.26 to 52.75 N, and from 0.37 to 7.01 N when predominantly SDF were included (Table 2). A negative correlation between fiber-enriched GF bread's crumb hardness and specific volume was established, regardless of the fiber type, confirming the higher crumb hardness of the densely and tightly packed crumb structure in GF bread loaves with low specific volumes [20,21,50,52,54,64,68,75,87].

A decline in crumb hardness was reported upon inclusion of rice and millet bran; oat, barley, maize, apple, sugar beet, and fine bamboo fiber; and insoluble yeast and fungi (1-3) (1-6)- β -glucan, implying a crumb-softening effect of these fibers considered as predominantly IDF when working at adopted water levels [17,20–22,54,64,74]. A positive IDF influence on crumb hardness can be associated with the presence of lipids, which form an amylose–lipid complex and affect starch gelation during baking, in the case of cereal brans as the fiber source [114]. Additionally, the corresponding effect can also be ascribed to the water-binding capacity of IDF, favoring a decline in moisture loss during storage due to the potential hydrogen bonding between fiber and starch, and consequently postponing starch retrogradation [17,18,21]. Conversely, with the addition of cellulose, wheat fiber and bran, apple pomace, and resistant starch, the hardening effect of GF bread's crumb was observed in spite of the water level adjustments [19,21,51,75]. This negative effect arises either from the restriction of available water in the GF batter system by IDF, which impedes batter development and rise, manifesting in the thickening of the walls, enveloping the air cells in the crumb and lower GF bread volumes [17,18,21,75], or from the presence of excess water in the system leading to the same result [17,63]. Moreover, in the case of oat bran, resistant starch, and orange pomace inclusion, the effect on the crumb hardness was dependent on the fiber amounts used. GF bread formulations with up to 5 or 10 g/100 g of oat bran and resistant starch [48,50], and 2 g/100 g of orange pomace [18] yielded breads with softer crumb, whilst a further increase in the content of these fibers exhibited the opposite effect.

GF breads with predominantly SDF, such as inulin, Nutriose[®], and polydextrose, principally exhibited decreased crumb hardness [20,50,51,87], whereas after the inclusion of β -glucan, some discrepancies were denoted [64,66,78]. A crumb-softening effect was reported upon the addition of the soluble yeast β -glucan, and with increasing the oat and barley β -glucan content up to 2.6 g/100 g [64,68]. Conversely, in the study of Ronda et al. [66], a crumb-hardening effect was observed after oat and barley β -glucan addition, with this effect being partially diminished by increasing water levels, but it should be noted that in the corresponding study, much higher amounts of β -glucan were included (up to 11.8 g/100 g), explaining these contradictory results [66]. It is assumed that the presence of predominantly SDF can decrease starch's degree of crystallinity area, which further hinders the interaction between ungelatinized starch granules, leading to a softer GF bread crumb [51].

GF bread's springiness, representing the rate at which a deformed material is restored to its original condition after the withdrawal of a deforming force [113], ranged between 0.72 and 1 for predominantly IDF- [20,51,54,74] and between 0.79 and 5.5 for predominantly SDF-containing breads [20,51,66,87]. Generally, GF bread's springiness was not significantly affected by the presence of fibers, regardless of type [20,64], except for the GF bread enriched with cellulose and resistant starch, which exhibited lower springiness values [48,75].

Cohesiveness is a texture parameter associated with the strength of the intrinsic bonds established between components [113]. Experimental values for GF bread cohesiveness varied between 0.21 and 0.89 for addition of predominantly IDF [20,51,55,74], and between 0.28 and 0.80 when predominantly SDF were included [20,51,66,87]. GF bread's cohesive-

ness decreased with increasing apple pomace levels [19], and incorporation of potato, pea, oat, and bamboo fiber, wheat bran and resistant starch (considered as predominantly IDF), as well as inulin, Nutriose[®], and polydextrose (considered as predominantly SDF) [20,51], whereas the presence of insoluble and soluble yeast and fungi β -glucan, and resistant starch derived from tapioca and maize did not affect this parameter [48,64]. As observed, a straightforward effect regarding different fiber types (IDF or SDF) on GF bread cohesiveness could not be established.

The energy required to chew a solid food product to a state ready for swallowing is described by chewiness [113]. GF bread's chewiness values varied between 0.17 and 7.70 N for predominantly IDF- [17,54,64,74], and between 0.26 and 6.24 N for predominantly SDF-containing breads [64,66,87]. Commonly, chewiness follows a similar trend as perceived for crumb hardness, which is expected, considering the direct relation between these parameters [17,66]. Accordingly, in GF bread enriched with apple and sugar beet fibers, insoluble and soluble yeast and fungi β -glucan, and with inulin, a decline in chewiness was reported [17,64], while the addition of wheat bran, resistant starch, and oat and barley β -glucan increased this parameter [51,66].

Resilience is a texture parameter with a higher sensitivity than springiness and cohesiveness, quantifying the instant recovery capacity after crumb compression, unlike the latter two parameters estimating the recovery capacity after a waiting (recovery) time [64]. Experimental values for resilience ranged between 0.17 and 0.38 in GF bread with predominantly IDF [17,19,54,64], and between 0.29 and 0.38 when predominantly SDF were added [64,66,87]. The inclusion of predominantly IDF, such as millet bran, apple and sugar beet fibers, apple pomace, and insoluble yeast and fungi β -glucan, induced a decline in GF bread resilience [17,54,64,66]. GF bread's resilience was not affected by the addition of predominantly SDF, such as inulin and soluble yeast β -glucan, whilst incorporation of oat and barley β -glucan resulted in a decrease of this parameter [64,66,87].

As evidenced by the discussed results, apart from the exerted influence of fiber type (IDF or SDF) and quantity, the presence or restriction of available water should be counted as one of the major factors affecting GF bread's crumb texture, particularly its hardness.

5. Sensory Properties of Fiber-Enriched Gluten-Free Bread

Judgment of the overall product quality involves its sensory properties, in terms of both technological attributes (color, volume, texture) as well as the product's taste and odor, considering that the sensory acceptance of a new product by consumers is crucial for bringing the product to market. Sensory evaluation of GF bread is commonly performed 2 h after baking [51,53] but also after 24 h [17]. Sample preparation usually involves bread slicing (10–20 mm) and 3-digit sample coding [17,22,51]. Bread slices are primarily intended for mouthfeel and taste evaluation, and additional whole-bread and half-bread samples could be introduced for appearance and tactile sample assessment [53]. Evaluation is conducted at normal lighting conditions at room temperature (25 °C) with breaks between randomized sample supply for palate rinsing with water [17,51,53].

The samples' sensory evaluation is performed by the sensory evaluation panel, which could consist of untrained or trained panelists, commonly in the age range of 20–55 years and with an approximately equal gender distribution [51]. The untrained panelists were usually habitual bread consumers and their numbers in the panel were between 20 and 73 persons [22], while the panel comprising trained panelists included 6–10 persons [17,21,48,51].

The overall acceptability or acceptance test for GF bread addresses its appeal to consumers based on sensations related to looking and tasting. A nine-point hedonic scale (1: dislike extremely, 5: neither like nor dislike, and 9: like extremely) is commonly used for the acceptability assessment, as well as evaluation of the GF bread's quality attributes, such as appearance (shape, color, surface, and crust properties), color, odor, taste, and texture [21,22,53]. In the corresponding scale, value 6.0 is considered as the minimal value for establishing the product as acceptable [51]. Additionally, self-developed [17] or standard [48] descriptive methods coupled with a five-point scale enabling descriptive data

quantification were also used for the sensory evaluation. Herein, the previously defined importance coefficients (IC) were introduced in order to gain reasonable overall acceptance, which is not equally affected by the quality parameters evaluated; appearance, crumb appearance and characteristics, and taste were denoted as the most influential [17,48]. The product is evaluated as acceptable by the descriptive method if the given score exceeds 56% of the maximal score [17]. Furthermore, GF bread attributes such as bitterness, firmness, chewiness, and dryness were also assessed by time–intensity evaluation trials [51].

The fiber source and the amount included in GF bread formulations reflect, to a high extent, on the final bread's quality and sensory attributes. According to the published studies dealing with the sensory evaluation of fiber-enriched GF bread, 20 g/100 g of fiber represents a boundary value providing the acceptability and desired quality of GF bread [17,21,22,48,51,53]. However, fiber origin/source also plays an important role in the corresponding limit setting. A discrepancy in this regard is noticed for resistant starches, where the addition of a corn and/or tapioca resistant starch of up to 20 g/100 g revealed no negative influence on the product's total quality score [48], while the addition of 7 g/100 g of resistant starch type IV (corn) yielded a product labeled as unacceptable [51]. This could be explained as a consequence of a chemical modification of the resistant starch applied in a smaller amount [51]. As regards to commercial fibers from rice bran as well as defatted rice bran, incorporation of 10 g/100 g resulted in significant enhancement of the GF bread's sensory attributes and the highest acceptance compared to the control [22]. Moreover, inulin inclusion in the amount of 7.5 g/100 g yielded a GF bread that was evaluated as more appealing compared to the control [51]. Furthermore, the highest sensory evaluation scores for GF bread were obtained upon the addition of sugar beet and apple fibers in amounts of 3, 5, and 7 g/100 g coupled with 4 g/100 g HPMC, taking into account that the HPMC content was established as the leading factor affecting bread quality [17]. Incorporation levels of 1–3 g/100 g examined for maize and potato fiber in GF formulations were denoted as the ones with the highest overall acceptability scores, as well as enhancement in almost every quality attribute [21,53].

6. Nutritional Quality of Fiber-Enriched Gluten-Free Bread

DF were initially introduced as one of the strategies to enhance the nutritional deficiency of GF products, besides their influence on technological and sensory quality improvement [115]. When diagnosing celiac disease, DF deficiency is associated with malabsorption due to intestinal villi atrophy, whereas following up GF diet, a lack of fiber intake is predominantly linked with poor GF product quality and avoidance of foods that are naturally without gluten and high in fiber [116]. The basic ingredient composition of GF products is responsible for the reduced DF intake, because the main constituents of these products are various starches and refined flours with low fiber content [117]. Apart from DF deficiency, GF products are also characterized by low content of protein, calcium, iron, and other minerals, as well as folate and vitamins, while high amounts of fat, sugar, and sodium are observed compared to wheat counterparts [115,117–119]. Besides addressing DF deficiency, inclusion of DF such as inulin and fructooligosaccharides in calcium-fortified GF bread could increase cellular calcium uptake [120], as well as improve iron absorption from nondissociable dietary supplements in the upper intestine of celiac disease patients [121].

Determination of the TDF content in food is usually based on enzymatic treatment, where commonly applied methods are the AACC method 32-07 [111] and the AOAC method 991.43 [122], which involve the application of commercially available test kits [17,21,50].

Variations in the DF content in commercially available GF breads are significant, as shown by conducted studies [123,124]. The interval includes a DF content of 0 to 11.7%, with an average value of 5.19% [123]. Hence, the corresponding values in GF breads are higher, similar, or lower compared to wheat breads [125–127]. The mentioned discrepancy is usually attributed to the presence of hydrocolloids as structure-forming ingredients in GF breads, which nutritionally fall into the DF category [123].

Although many studies dealt with GF bread enrichment by DF (Table 1), scarce results are present regarding the DF content in the obtained GF products, which is highly dependent on the amount and purity of the DF added. The corresponding studies revealed that DF content in enriched GF breads is in the range of 1.5 to 12.3% [50,59,76,128]. The reported TDF content in GF breads with the addition of 3 and 7 g/100 g sugar beet fibers was 4.98 and 6.07%, respectively, while for 3 and 7 g/100 g of apple fibers, the TDF content was 4.56 and 5.89%, respectively [17]. Furthermore, higher TDF values of 7.57 and 12.24% were determined for GF bread enriched with 5 and 10 g/100 g oat fiber, as well as with 7.56 and 12.31 g/100 g resistant starch, respectively [50]. Additionally, cereal fiber supplementation of 9 g/100 g (wheat, maize, oat, and barley) gave 7% TDF content in the obtained breads [21]. Regarding the addition of cereal bran, a significant increase in DF content of 5.97% was noticed for GF bread containing 10 g/100 g of commercial rice bran (Rifiber) [22]. Nevertheless, the introduction of 5 and 10 g/100 g inulin resulted in a lower TDF content of 3.49 and 4.50% [50], while the addition of 5.5 g/100 g orange pomace led to 4.2% TDF in the GF bread [18]. The incorporation of 10, 15, and 20 g/100 g of individual resistant starch (maize or tapioca), as well as a maize/tapioca resistant starch mixture in the same amounts delivered a gradual increase in the bread's TDF content from 4.97 to 6.3% for corn resistant starch, from 3.61 to 4.31% for tapioca resistant starch, and from 4.01 to 5.20% for a mixture of the corresponding starches in equal amounts [48]. Additionally, inulin and oat β -glucan content of 1.5% was detected in GF breads after their inclusion in formulations, 5 g/100 g and 5.6 g/100 g, respectively [59,76], while the addition of 12 g/100 g inulin-type fructans yielded GF breads with 8% inulin-type fructans and 11% TDF [77].

The current regulation in Europe (Regulation (EC) No 1924/2006) [129] provides ways to label DF in products with respect to their minimal content. Hence, food can be labeled as "source of fiber" if it contains 3% fiber and as "high fiber" if it contains 6% fiber. According to the summarized results herein, the majority of GF bread formulations enriched with DF can bear the attribute "source of fiber", while fewer can be described as "high fiber" food.

7. Conclusions

The determination of pertinent values for all fundamental rheological parameters that will enable the production of GF bread with the desired quality still represents a major challenge, and fiber inclusion makes this task even more complex. At adopted hydration levels, the strengthening of GF batter's structure upon IDF addition and the increase in viscous behavior after SDF inclusion are general models fulfilled when fibers of similar composition, origin, molecular weight, and degree of polymerization are compared. Accordingly, increased specific volumes and softer GF bread crumb can be attained, with this enhancement more pronounced after SDF addition, as a consequence of more uniform and aerated GF batter structure. However, many exceptions can appear in fiber-enriched GF formulations that involve other diverse structuring ingredients and different water levels.

The perceived attractiveness of fiber-enriched GF breads in terms of sensory attributes can be considered as enhanced in most cases, regardless of the fiber added, while the optimal quantity of fibers providing this enhancement can be set to 7 g/100 g, as established upon the presented literature review. In many studies investigating GF bread enrichment with fibers, the nutritional composition of the end product is lacking. However, in the studies that conducted proximate composition analysis, an increase in TDF content is achieved enabling the labeling of GF bread as a "source of fiber" or "high in fiber", depending on the added fiber amount and purity.

Producing GF batters with balanced tensile and elastic characteristics is essential for reaching optimal baking performance and can be attained when added fiber type (insoluble/soluble) and levels are in concordance with other GF batter constituents. Bearing this in mind, the summarized influence of DF on GF bread quality could be interpreted through an iceberg model. The visible part above the water line can represent the influence of fiber type, quantity, and water level adjustments, which are predominantly investigated, whilst the underwater part can include the effects of fiber origin, structure, degree of

polymerization, and molecular weight, investigated and explained to some extent, and fiber interactions with other batter constituents, which are not clearly understood and demand further research.

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