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NUTRITIONAL AND TECHNOLOGICAL QUALITY OF GLUTEN-FREE BREADS FORMULATED WITH NON-CONVENTIONAL FUNCTIONAL FLOURS/POWDERS/EXTRACTS- A REVIEW

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ABSTRACT
Production of high quality and nutrient-rich gluten-free (GF) bread remains a challenge for food scientists. Incorporation of new functional ingredients is one of the main approaches to improve the acceptability of GF bread by consumers. This review highlights recent studies (2016-to present), adopted to improve the nutritional and technological quality of GF bread with the help of non-conventional functional ingredients, edible insect powder/flour, microalgae and seaweed powders, green mussel, bee pollen, anchovy flour, coffee/cocoa by-products, and leaf powder/extract. The scientific studies reviewed in this paper demonstrated that those non-conventional ingredients provided nutritional and technological functionality to the GF bread in different manners. They acted as coloring, flavoring, antioxidant, texturizing, or anti-staling agents in GF bread formulations. These non-conventional functional ingredients have the potential to produce nutrient-rich GF bakery products with improved quality.

1. Introduction

Gluten-containing grains have been an important item of human diet for more than 10,000 years (Cabanillas, 2019) and are also expected to remain important in human diet for many years. Despite its ubiquity, gluten intake causes disorders in humans in the prevalence of 1-13% of the population, such as wheat allergy (allergic), celiac disease (auto-immune), dermatitis herpetiformis (auto-immune), gluten ataxia (auto-immune) and gluten sensitivity (immune-mediated) (Gao *et al*., 2018). The most effective treatment known to reduce or prevent the side effects of gluten-related disorders is a lifelong gluten-free (GF) diet. GF bakery products are part of the GF diet, and their nutritive value and quality are significant concerns. Among the bakery products, the production of high quality and nutritious GF bread is still a challenge (da Rosa Machado and Thys, 2019). The main challenges related to GF bread can be divided into technological and nutritional issues related to the absence of gluten and insufficient nutrient-rich ingredients in GF bread formulations.

Gluten is a functional component in bread formulations in terms of technological quality, due to its unique structure-forming properties during processing (El Khoury *et al*., 2018). Since gluten is responsible for the elastic properties of bread, its porous structure and volume; absence of gluten in bread formulations induces GF breads with low quality, such as low volume, crumbling texture, dense and dry structure, high crumb hardness, lighter crumb and crust color, poor flavour and mouthfeel, and rapid staling (Naqash *et al*., 2017). Furthermore, since GF breads prepared with conventional ingredients usually have high caloric value and glycemic index and unsatisfactory nutritive value, development of healthy GF breads with balanced nutrients is still a challenge (Javaria *et al*., 2016). Recipe and technology-based approaches have been applied to cope with these common problems (Naqash *et al*., 2017).

Various conventional and non-conventional GF ingredients have been incorporated in GF breads to mimic gluten network and improve their nutritional quality. Conventional ingredients used in GF breads are GF cereal and pseudocereal flours, legume, seed and nut flours, starches and proteins, protein isolates and concentrates from different GF sources. Edible insect powder/flour, microalgae and seaweed powders, green mussel, bee pollen, anchovy flour, coffee/cocoa by-products, and leaf powder/extracts are the recently investigated non-conventional functional ingredients used in GF bread formulations.

Edible insects are cheap, environmentally friendly protein-rich materials with biological activity (e.g., cricket powder has ability to reduce inflammation, and support intestinal microflora) (Kowalczewski *et al*., 2021). GF bread has been one of the application areas of edible insects to produce value-added products (da Rosa Machado and Thys, 2019; Kowalczewski *et al*., 2019, 2021; Nissen *et al*., 2020). Eukaryotic microalgae and prokaryotic cyanobacteria; both commonly referred as microalgae and macro-forms such as seaweeds are photosynthetic organisms in the group of algae with functional bioactive compounds (Lee, 2008; Renuka *et al*., 2018). The microalgae genera, *Spirulina*, *Botryococcus*, *Chlorella*, *Dunaliella*, *Haematococcus*, and *Nostoc* have ability to produce bioactive compounds providing antioxidant, antimicrobial and anti-inflammatory activities (Morais *et al*., 2015). Those functional properties make microalgae one of the promising sources of functional food ingredients (Gouveia *et al*., 2008; Buono *et al*., 2014). Besides their nutritional functionality in food products, microalgae can be used as texturizing ingredients. The structural biopolymers of photoautotrophic microalgae, such as proteins, storage polysaccharides and cell wall related polysaccharides have ability to alter textural properties of the fortified food products (Bernaerts *et al*., 2019). One of the promising application areas of microalgae to produce functional foods is GF bakery products (Diprat *et al*., 2020; Khemiri *et al*., 2020; Nunes *et al*., 2020). Seaweeds are marine macroalgae that contain excellent sources of bioactive components like dietary fibers, carotenoids, essential fatty acids, proteins, minerals, and vitamins (Barba, 2017; Lopez-Santamarina *et al.*, 2020; El-Sheekh *et al*., 2021). Seaweeds have been added to GF formulations to benefit those functional compounds and improve nutritional quality of GF breads (Rózylo *et al*., 2017). Since green mussel is a functional ingredient that contains bioactive components and proteins (Vijaykrishnaraj *et al*., 2015); bee pollen is also a natural functional food and food ingredient due to its nutritional properties and health benefits (Thakur and Nanda, 2020) and anchovy flour consists of valuable components, such as essential fatty acids and amino acids, and minerals (Yılmaz and Koca, 2020), they are potential ingredients to be used in GF bread formulations to improve nutritive value. Addition of coffee by-products provide high fiber and antioxidant contents, which have positive impacts on colonic health, and make them functional (Gemechu, 2020). Coffee parchment is a by-product of coffee wet processing, used in food formulations not only for its antioxidant capacity and dietary fiber content but also for its antifungal activity (Klingel *et al*., 2020; Littardi *et al*., 2021). Cocoa bean shells are by-products of cocoa processing with nutritional components. They are rich in dietary fiber, polyphenols, and antioxidants (Okiyama *et al*., 2017). Besides their nutri-functional properties, they have also been added to bakery products for their techno-functional characteristics, such as their role as fat replacers, texturizing, or anti-staling agents (Collar *et al*., 2009). Fruit, vegetable-based by-products are considered as low-cost potential sources of valuable ingredients, such as proteins, vitamins, and minerals as well as dietary fibre and bioactive compounds (Bedrníček *et al*., 2020; Sedlar *et al*., 2021; Krupa-Kozak *et al*., 2021; Vacca *et al*., 2023). In addition, fruit, vegetable, and leaf powders have been found to be effective to control retrogradation of starchy foods in literature (Salehi and Aghajanzadeh, 2020; Park *et al*., 2021).

2. Functional Non-Conventional Ingredients

2.1. Edible insect powder/flour

Edible insects have been added to GF bread formulations to produce value-added protein-rich products (da Rosa Machado and Thys, 2019; Kowalczewski *et al*., 2019, 2021; Nissen *et al*., 2020) (Table 1). Addition of cricket powder (*Gryllus assimilis*) to the formulation increased protein and lipid contents of GF breads and provided darker crumb and crust color (da Rosa Machado and Thys, 2019). The results indicated that incorporation of 20% cricket powder doubled the protein content of GF bread. The high water and oil holding capacities of cricket powder provided acceptable technological properties, such as increased porosity and cell density, to GF breads, which is related to high protein and lipid contents of insect powders (da Rosa Machado and Thys, 2019) (Table 1). On the other hand, cricket powder fortified GF breads presented crumbs with higher hardness and chewiness values than the control GF bread. However, removal of canola oil from the cricket powder fortified GF bread formulation decreased hardness and chewiness and increased cohesiveness values providing similar characteristics to the control sample. The emulsifying properties of cricket proteins ensured reduction in hardness and chewiness values and increase in crumb consistency and cohesiveness values to GF bread, reflecting internal cohesion of the crumb (Kowalczewski *et al*., 2019). Nissen *et al.* (2020) incorporated cricket flour to sour dough bread formulation as protein source. They determined the volatile compounds, protein profile and antioxidant activity of GF sourdough and bread. The results showed that cricket containing dough had similar fermentation process, typical flavoring profile and significantly higher antioxidant activity with the standard dough. Moreover, cricket GF bread obtained by LAB fermentation (equal mix of *L. sanfranciscensis* and *L. plantarum*) had proteins with high nutritional value and enhanced antioxidant activity (Nissen *et al*., 2020). Kowalczewski *et al.* (2021) investigated the nutritional value and biological activity of GF bread enriched with cricket powder. A two, four and seven-fold increase in protein content; 23%, 59%, and 105% increase in fat content was observed for GF breads formulated with 2%, 6% and 10% cricket powder, respectively. Additionally, they stated that replacement of starch with 10% cricket powder resulted in about three-fold and five-fold increase in the content of insoluble dietary fiber and the total polyphenolic compounds, respectively. The undesirable activity of β-glucuronidase was reduced by 65.9% in the small intestine and up to 78.9% in the large intestine with the use of cricket powder at 10%.

2.2. Microalgae and seaweed powders

Microalgae have high protein, lipid and bioactive content and texturizing ability in GF bakery products. Diprat *et al.* (2020) added *Chlorella sorokiniana* biomass powder at the concentrations of 2.5 and 5.0g per 100g of the blend of rice flour and corn starch in substitution of pea flour to increase the nutritional quality of GF bread. Fortification of GF bread with microalgae provided greenish color, higher protein, carotenoids and polyunsaturated fatty acids content without changing specific volume and textural characteristics of them. It has been stated by Khemiri *et al.* (2020) that the addition of two green microalgae species (*Nannochloropsis gaditana* L2 and *Chlamydomonas sp.* EL5) significantly increased the protein, lipid and ash contents of GF bread. A particular increase in linolenic acid (18:3, ω3) and a decrease in ω3/ω6 ratio had been observed. The pigments in microalgae significantly changed the color of dough, bread crust and crumbs. The high protein content of green microalgae ensured formation of strong texture (decreased crumbliness) by increasing firmness and adhesiveness parameters of GF bread (Khemiri *et al*., 2020). Nunes *et al.* (2020) fortified GF bread with *Tetraselmis chuii* at concentrations of 1%, 2% and 4%. Low contents of *T. chuii* in the formulation destabilized the network formed by starch and HPMC, resulting in low bread volume, high firmness and more compact crumb. Addition of microalgae at the highest concentration (4%) increased the capacity of bread dough to retain the gas bubbles providing higher bread volume and softening effect which competes with the structure of control GF bread. Moreover, the improved bioactivity (higher total phenolic content and antioxidant capacity) of GF breads fortified with 4% *T. chuii* make them healthy GF food alternatives with interesting taste and colour (Nunes *et al.*, 2020).

Seaweeds have been added to GF formulations to improve nutritional and technological quality of GF breads (Rózylo *et al*., 2017). Rózylo *et al.* (2017) added brown algae (*Ascophyllum nodosum*) powder in the amounts of 2%, 4%, 6%, 8%, and 10% of the total flour (white rice, corn and millet flour) content to determine physical, antioxidant, and sensory properties of fortified GF bread. Brown algae fortification increased volume, elasticity, antioxidant activity and antiradical potential and decreased firmness and crumb staling degree of GF breads. The decrease in firmness and crumb staling degree of GF breads could be due to the interaction of algae components with starch in GF flours and decreasing the starch chain interactions. Since over-addition of brown algae powder resulted in an unpleasant taste, the researchers suggested addition of 2% or 4% algae powder to obtain acceptable GF bread (Rózylo *et al*., 2017).

2.3. Green mussel

Green mussel is known to have functional ingredients, such as bioactive components and proteins that make it applicable to be used in food formulations (Vijaykrishnaraj *et al*., 2015). Vijaykrishnaraj *et al.* (2016) added green mussel (*Perna canaliculus*) protein hydrolysates to optimized GF bread formulation (70:20:10 (buckwheat flour: rice flour: chickpea flour)) at the concentrations of 5%, 10%, 15%, 20% on flour weight basis and the quality of fortified GF bread and the peptides responsible for mussel flavour were characterized. Volume of all GF breads was lower, and firmness of them were higher than that of wheat bread (control 1). The reduction in volume was mainly related to absence of gluten in GF formulations. On the other hand, the volume of fortified GF bread up to 20% level was higher than that of GF control bread (control 2, GF bread without green mussel protein hydrolysate), which is related to the interactions between protein and starch components. Addition of mussel protein hydrolysates improved bread swelling and gelling properties and crumb structure significantly (Table 1) with the help of starch-protein interactions. According to the sensory evaluation, GF breads formulated with green mussel protein hydrolates had a mussel flavour, and after taste, it was also noticeable, which was accepted by the sensory panelists. Since protein hydrolysates from green mussel do not contain allergenic proteins, they can be used as alternative natural flavouring agents in GF food systems (Vijaykrishnaraj *et al*., 2016).

2.4. Bee pollen

Bee pollen is known as a natural functional food and food ingredient due to its nutritional properties and health benefits (Thakur and Nanda, 2020). Conte *et al.* (2018, 2020) added bee pollen to GF bread formulations to improve nutri- and techno-functional properties and aroma of GF bread (Table 1). The results obtained by Conte *et al.* (2018) indicated that bee pollen supplementation from 1% to 5% did not significantly change either dough machinability or gassing power ability during fermentation and provided a well-leavened dough system. Bee pollen addition to bread formulation at medium-high levels (3-4%) improved the technological quality of GF bread providing higher specific volume, darker color, softer, more cohesive and resilient crumb, more homogeneous crumb grain structure, and lower and slower staling kinetics compared to the GF control bread. Bee pollen-fortified samples at medium-high levels showed the highest values of dough area expansion during the proofing process, resulting in GF breads with the highest specific volume. The dark color observed for pollen-fortified GF breads was related to non-enzymatic browning reactions occurred during baking, in which the components of pollen, such as reducing sugars act as substrates in those reactions. Furthermore, the flavonoids and carotenoid pigments found in pollen may have also been contributed to the color of crust. Lower hardness values and the slower firming rate observed in all the fortified breads (up to 4%) was related to the presence of natural emulsifiers (especially monoglycerides) and amylases in the pollen (Conte *et al*., 2018). The interaction of emulsifiers with starch prevents starch retrogradation and contributes to lower crumb firming. Amylases, the starch-modifying enzymes decreases starch-chain length providing less starch-chain interactions and lower firming rate. The overall acceptability of GF breads fortified with bee pollen at medium-high levels was found to be higher than for the control (Conte *et al*., 2018). Conte *et al*. (2020) found that incorporation of bee pollen at the highest levels (4-5%) to the formulation increased proteins, the minerals; K and Ca, soluble and bioaccessible polyphenols, total carotenoids, antioxidant activity and improved aroma composition of GF breads, significantly. Although 48 volatile compounds were found in the fortified breads, only 5, namely pyrazinamide, 5-methyl-2-furaldehyde, 2-acetylfuran, furfural, 2-pentyl-furan, were related to bee polen supplementation by the authors (Conte *et al*., 2020).

2.5. Anchovy flour

Anchovy flour consists of valuable components, such as essential fatty acids and amino acids, and minerals (Yılmaz and Koca, 2020). Yılmaz and Koca (2020) fortified GF corn bread with anchovy (*Engraulis encrasicolus*) flour at the levels of 10, 20, 30 and 40% (corn flour basis) (Table 1). Anchovy flour addition improved nutritional properties of GF corn bread in terms of essential fatty acids (especially ω-3 fatty acids, EPA and DHA), aminoacids and minerals due to its nutritious nature. In terms of technological quality, anchovy flour-fortified GF breads exhibited lower lightness values for crust and crumb and lower hardness and chewiness values, related to their fat-rich composition. The high protein and fat content of anchovy flour contributed to improved chewing properties, desirable bread structure and shape, color, and taste, resulting in highly acceptable sensory properties (Yılmaz and Koca, 2020).

2.6. Coffee/cocoa by-products

Coffee/cocoa by-products are also regarded as promising functional ingredients to improve nutritional and technological quality of GF breads (Guglielmetti *et al*., 2019; Rinaldi *et al*., 2020; Rios *et al*., 2020; Littardi *et al*., 2021). Addition of coffee by-products provide high fiber and antioxidant contents, which have positive impacts on colonic health, and make them functional (Gemechu *et al*., 2020). Coffee silverskin (rich in dietary fiber and present high antioxidant activity) and coffee husk (rich in dietary fiber and phytochemicals) extracts improved nutritional properties, such as dietary fiber content, antioxidant capacity, of GF breads (Guglielmetti *et al*., 2019). Moreover, the authors considered coffee silverskin and husk extracts as natural colorants for GF bread providing the typical appearance of wholemeal bread. Addition of isolated coffee cascara dietary fiber improved nutritional and physicochemical properties of GF bread and provided good sensory profile (Rios *et al*., 2020).

Table 1. Improvements achieved in the nutritional and technological quality of GF breads with the help of functional non-conventional ingredients -Recent studies (2016-to present)

Functional Ingredient / Concentration	**Other ingredients**	**Main improvements**	**Reference**
Cricket powder (*Gryllus assimilis*) / (10, 20%)	Rice flour, corn starch, xanthan gum, CMC	higher protein and lipid contents, darker crumb and crust color, higher porosity and cell density	da Rosa Machado and Thys, 2019
Cricket powder / (2%, 6% and 10%)	Corn starch, potato starch, guar gum, pectin	lower hardness and chewiness values, higher crumb consistency and cohesiveness values	Kowalczewski *et al.*, 2019
Cricket powder / (2%, 6% and 10%)	Corn starch, potato starch, guar gum, pectin	higher protein, polyunsaturated fatty acids, insoluble dietary fiber and mineral contents; increased antioxidant activity and decreased β-glucuronidase activity	Kowalczewski *et al.*, 2021
Cricket flour	Corn flour, rice flour, HPMC	higher protein content and antioxidant properties	Nissen *et al.*, 2020
Chlorella sorokiniana / (2.5 and 5.0g/100g rice flour and corn starch basis in substitution of pea flour)	Rice flour, corn starch, pea flour, xanthan gum, CMC	higher protein, carotenoid and polyunsaturated fatty acid contents	Diprat *et al.*, 2020
Nannochloropsis gaditana L2 and *Chlamydomonas sp*. EL5 / (1.0 and 3.0 g/100 g of rice, buckwheat flour and potato starch)	Rice flour, buckwheat flour potato starch, HPMC	higher protein, lipid and ash contents, darker crumb and crust color, improved structural properties (strong texture)	Khemiri *et al.*, 2020
Tetraselmis chuii / (1, 2 and 4%)	Rice flour, buckwheat flour, potato starch, HPMC	higher bioactivity (total phenolic content and antioxidant capacity), innovative green appearance at 4% level.	Nunes *et al.*, 2020
Brown algae (*Ascophyllum nodosum*) powder / (2, 4, 6, 8 and 10%)	White rice, corn and millet flour	higher volume, elasticity, lower firmness, lower crumb staling degree, antioxidant activity and antiradical potential	Rózylo *et al.*, 2017
Green mussel (*Perna canaliculus*) protein hydrolysates / (5, 10, 15, 20%)	Buckwheat flour, rice flour, chickpea flour	higher volume and mussel flavour in GF breads	Vijaykrishnaraj *et al.*, 2016
Bee pollen / (1, 2, 3, 4, 5%)	Rice flour, corn starch, guar gum and Psyllium fiber	higher specific volume, darker color, softer, more cohesive and resilient crumb, more homogeneous crumb grain structure, and lower and slower staling kinetics with the incorporation of medium-high levels (3-5%) of bee pollen	Conte *et al.*, 2018
Multifloral bee pollen / (1, 2, 3, 4, 5%)	Rice flour, corn starch, guar gum and Psyllium fiber	higher protein, K and Ca contents, improved bioactive properties and aroma composition	Conte *et al.*, 2020
Anchovy flour / (10, 20, 30, 40% on corn flour basis)	Corn flour, xathan gum, vegetable mix (chard, leek, onion)	higher protein, fat, essential amino acids (lysine and tryptophan), Omega-3 (EPA + DHA), Ca, Fe, K, P, Zn and Se contents, highly acceptable sensory and textural properties	Yılmaz and Koca, 2020

Abbreviations: CMC, carboxy methyl cellulose; HPMC, hydroxy propyl methyl cellulose; EPA, Eikosapentaenoic acid; DHA, Docosahexaenoic acid

Table 1. Improvements achieved in nutritional and technological quality of GF breads with the help of functional non-conventional ingredients -Recent studies (2016-to present) (CONTINUED)

Functional Ingredient / Concentration	Other ingredients	Main improvements	Reference
Coffee silverskin extract, coffee husk extract / (2.5% d.m.)	Commercial premix (mainly composed of corn starch), inulin, rice protein	higher dietary fiber content and antioxidant capacity	Guglielmetti *et al*., 2019
Isolated coffee cascara dietary fiber / (3.0, 4.5%)	Commercial premix, rice protein	higher dietary fiber and protein contents, higher dough yield and crumb moisture, higher color intensity and crumb elasticity, lower crumb firmness and estimated calorie values, good sensory profile	Rios *et al*., 2020
Green coffee parchment / (2%)	Commercial GF bread mixture (corn starch, rice flour, vegetable fibers (psyllium, bamboo), whole rice flour, lentil flour, HPMC)	higher antioxidant capacity, oxidative stability, darker color and lower presence of HMF	Littardi *et al.*, 2021
Cocoa bean shell added at three different dimensional fractions (F1 (1.00-1.99mm), F2 (0.50-0.99mm) and F3 (0.355-0.490mm)) / (4%)	Commercial GF bread mixture (corn, rice cream soup, tapioca starch, vegetable fibers, guar flour and HPMC)	pleasant darker color, antistaling effect (for F1 fraction)	Rinaldi *et al*., 2020
Moringa oleifera leaf powder / (2.5, 5.0, 7.5, 10.0%)	Rice/field bean semolina	higher total phenolics content and antioxidant activity	Bourekoua *et al*., 2018
Fried onion (FO), dried onion (DO) and onion peel (OP) powders / (5%)	unhusked white buckwheat flour, corn flour, rice flour, linseed flour	higher flavonol and total phenolic contents and in vitro antioxidant activity	Bedrníček *et al*., 2020
Broccoli leaf powder / (5%)	Corn starch, potato starch, pectin	higher protein and mineral contents, improved specific volume and bake loss, improvement of antioxidant potential and anti-glycation end-products activity	Krupa-Kozak *et al*., 2021
Control dough with (YB-AE) and without (YB) artichoke leaf extract and Sour dough with (SB-AE) and without (SB) artichoke leaf extract / (6%)	Rice flour	highest antioxidant activity and highest scores of hydrocinnamic acid and cyclohexanecarboxylic acids for SB-AE containing GF breads	Vacca *et al*., 2023

Abbreviations: HPMC, hydroxypropyl methyl cellulose; HMF, hydroxymethyl furfural

Coffee cascara dietary fiber-fortified breads exhibited significantly higher dietary fiber and protein contents than the control bread. The addition of isolated coffee cascara dietary fiber increased dough yield and crumb moisture, related to water absorption ability of dietary fibers. Moreover, increase in color intensity and crumb elasticity and decrease in crumb firmness had been observed for fortified breads. Estimated calorie values of dietary fiber-fortified breads were found to be lower than control breads. According to sensory analysis, it was observed that the flavor “cereal” significantly masked in breads formulated with isolated coffee cascara dietary fiber by its “toasted (crust)”, “bitterness”, “sourness” attributes (Rios et al., 2020). Coffee parchment is a by-product of coffee wet processing, used in food formulations not only for its antioxidant capacity and dietary fiber content but also for its antifungal activity (Klingel et al., 2020; Littardi et al., 2021). Littardi et al. (2021) fortified GF breads with 2% green coffee parchment to improve nutritional and technological characteristics of them. Addition of green coffee parchment provided high antioxidant capacity, oxidative stability, and lower presence of hydroxymethylfurfural (HMF) to GF breads. Fortified breads had similar sensory characteristics, volume, moisture content, water activity, hardness, cohesiveness values and staling degree, but darker color compared to the control breads. Besides their nutri-functional properties, cocoa bean shells have been added to bakery products for their techno-functional characteristics, such as acting as fat replacers, texturizing agents, or anti-staling agents (Collar *et al*., 2009). Rinaldi et al. (2020) added cocoa bean shell at different dimensional fractions (F1, 1.00-1.99 mm; F2, 0.50-0.99 mm; F3, 0.355-0.49 mm) to produce functional GF bread. The water binding capacity, water absorption index, water holding capacity, water solubility index and proximate composition of cocoa bean shell fractions were found to be different which affects the functions of them on GF bread quality. Incorporation of cocoa bean shell negatively affected the crumb grain, specific volume, and moisture content of GF breads, but the results indicated that cocoa been shell fortified GF breads had pleasant dark color. Furthermore, F1 gave the lowest hardness value 3 days after storage, demonstrating an antistaling effect probably due to its high-water absorption index value, which could help to prevent the retrogradation of amylopectin. Authors suggested the use of cocoa bean shell fraction F1, in GF bread formulations, as a functional ingredient with limited impacts on fresh and stored bread quality.

2.7. Leaf powder/extract

In recent years, the nutri- and techno-functional aspects of vegetable by-products have made them alternative components of GF bread formulations (Bourekoua *et al*., 2018; Bedrníček, *et al*, 2020; Krupa-Kozak *et al*., 2021; Vacca *et al*., 2023).

Moringa *oleifera* leaf powder is one of the nutri-functional ingredients that has been added to GF bread formulations. Addition of *Moringa oleifera* leaf powder at the amounts of 2.5, 5.0, 7.5 and 10% significantly improved nutritional quality of GF breads by increasing total phenolic contents and antioxidant activity of them, related to their phytonutrients (Bourekoua *et al*., 2018). GF breads fortified with *Moringa oleifera* leaf powder at 2.5% considered the most acceptable GF bread with improved nutritional quality, exhibiting acceptable darker crumb and crust color, lower hardness and chewiness values compared to control GF bread and similar sensory characteristics with control GF bread. On the other hand, incorporation of leaf powder higher than 2.5% level resulted in low specific volume, compact texture, and low overall acceptability (related to taste, aroma, and appearance) compared to control GF bread.

In another study by Bedrníček, *et al*. (2020), powders of three onion waste fractions (fried onion (FO), dried onion (DO) and onion peel (OP)) were used for the preparation of GF bread with improved health benefits. The authors reported that all kinds of onion waste significantly increased the content of flavonols, total phenolic content and the in vitro antioxidant activity of GF breads. Among the onion wastes, 5% onion peel powder addition provided the highest flavonol and total polyphenol content and antioxidant activity in GF bread without any sensory changes. Moreover, as an indicator of good bioavailability of flavonols, the antioxidant activity in consumers' blood significantly increased with the consumption of OP-bread (Bedrníček, *et al*., 2020).

Broccoli (*Brassica oleracea* var. *italica*) leaves are characterized by a high content of nutrients (proteins, vitamin C, minerals, and trace elements) and bioactive compounds (glucosinolates, phenolic acids, and flavonoids), making them one of the promising functional GF components (Krupa-Kozak *et al*., 2021). Krupa-Kozak *et al*. (2021) investigated the suitability and functionality of broccoli leaf powder (BLP) as a GF component in GF bread. Incorporation of broccoli leaf powder at the level of 5% provided higher protein and mineral contents, higher specific volume, lower bake-loss, higher antioxidant potential and anti-glycation end-products activity to fortified breads, but similar hardness values with control GF breads (Krupa-Kozak *et al*., 2021).

The artichoke plant (*Cynara carduncul*us L.) has been considered as a healthy food in literature due to its antioxidant and bioactive properties. Artichoke leaf, one of the by-products of artichoke plant, have also been indicated as phenol-rich materials with antioxidant and anti-inflammatory properties (Vacca *et al*., 2023). In a study by Vacca *et al*. (2023) powder extract of artichoke leaf was combined with sourdough technology to improve nutritional and healthy features of GF bread. They stated that the incorporation of powder extract of artichoke leaf (6%) in GF sourdough bread formulation provided more than 15-fold and10-fold increase in DPPH (2,2-diphenyl-1-picrylidrazyl) and antioxidant activity values, respectively. Moreover, the highest anti-inflammatory effectiveness was found for artichoke extract added sourdough GF breads (Vacca *et al*., 2023).

3. Conclusions and Future Prospects

According to the results, it can be concluded that non-conventional functional ingredients have the potential to produce nutrient-rich GF bakery products with improved quality. Natural bioactive compounds exist in cricket flour, microalgae (*Tetraselmis chuii*), brown seaweed (*Ascophyllum nodosum*) powder, bee pollen, green coffee parchment, coffee silverskin and husk extracts, broccoli and *Moringa oleifera* leaf, and onion peel powders and powder extract of artichoke leaf can enhance the antioxidant properties of GF breads. From the technological point of view, light crumb and crust color of GF bakery products formulated with conventional ingredients is a common quality problem. Natural pigments of non-conventional ingredients have the potential to solve this problem. Cricket powder (*Gryllus assimilis*), microalgae (*Tetraselmis chuii*), brown algae (*Ascophyllum nodosum*) powder, bee pollen, anchovy flour, coffee/cocoa by-products, broccoli, and *Moringa oleifera* leaf powders improved the color of GF bakery products, providing desirable dark crumb and crust colors. One of the other problems related to GF bakery products is their poor flavor. Satisfactory results have been obtained to improve the flavor of GF bread with the incorporation of green mussel (*Perna canaliculus*) protein hydrolysate and bee pollen to the formulation. Furthermore, cricket powder (*Gryllus assimilis*), green microalgae species (*Nannochloropsis gaditana* L2 and *Chlamydomonas sp*. EL5) and brown algae (*Ascophyllum nodosum*) powder have ability to act as texturizing agents in GF formulations. Since crumbly and weak structure is common deficiencies observed in GF bakery products, mainly GF bread, presence of texturizing and hydrocolloidal agents to mimic gluten functionality in GF formulations is very important to obtain quality. Staling is the other common and serious problem for GF breads.

The anti-staling functions of brown algae (*Ascophyllum nodosum*) powder, bee pollen, and cocoa bean shell are valuable and notable to meet the consumer expectations.

As a future trend, genetic engineering approaches such as genetic modification of yeasts and other microorganisms to improve the rheology and nutritive value of GF batter/dough, may be considered in combination with the current or new non-conventional ingredients to achieve more successful results in terms of GF bread quality.

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