

Review

Valorization of Microalgae as Multifunctional Protein Sources in Plant-Based Systems: Structural, Functional, and Processing Challenges

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Abstract

The growing demand for sustainable protein sources has intensified interest in plant-based food systems. Pulses are well established and recognized as nutritious, sustainable protein sources (~15–30% dry weight), rich in lysine and limited in cysteine, methionine, and tryptophan amino acids. In contrast, Spirulina is characterized by a complete amino acid profile, high protein content (~50–70% dry weight), and bioactive potential. This comprehensive review explores the role of Spirulina as a complementary protein source in plant-based systems, with emphasis on its structural, technofunctional, and processing characteristics. A literature analysis was conducted to identify advances, trends, and gaps in their incorporation into food matrices. The findings indicate that, despite their nutritional and functional advantages, the application of microalgae and beans remains constrained by sensory and technological challenges, such as off-flavors and textural issues. The combination of microalgae with pulse-based ingredients represents a promising strategy to enhance amino acid balance, improve functionality, and develop nutritionally enriched products. Studies addressing multi-component systems remain scarce, especially in bakery and flour-based applications, as well as in understanding synergistic interactions between microalgae and pulse proteins in food matrices. This review highlights the potential of microalgae as key ingredients in next-generation food formulations. It identifies critical gaps that must be addressed to enable their broader application in food products.

Keywords: Spirulina; alternative proteins; composite flours; functional ingredients; pulse; bakery applications



Academic Editor: Ana María Díez-Pascual

Received: 10 June 2026

Revised: 22 July 2026

Accepted: 27 July 2026

Published: 30 July 2026

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1. Introduction

The growing global population and shifting socio-demographics are increasing pressure on food systems to supply sustainable protein. This highlights the need to improve existing sources and develop alternative proteins while addressing environmental, nutritional, technological, and consumer-related challenges [1,2]. Recent literature positions

microalgae [3–5] and legumes, especially pulses such as beans, lentils, and chickpeas, as sustainable sources of plant protein. These are considered key pillars of future food systems, particularly in the context of alternative proteins and food security [6–9].

Along these lines, pulses and microalgae have gained increasing attention as a nutritious, affordable, and environmentally sustainable source of plant protein for both human consumption and animal feed [10,11]. In addition to protein, pulses are important sources of complex carbohydrates, dietary fiber, vitamins, minerals, and several bioactive compounds [11]. Although pulses present antinutritional factors, these compounds can be substantially reduced through pretreatment and processing methods [11]. Consequently, regular pulse consumption has been consistently linked to health benefits and a lower risk of chronic non-communicable diseases, including obesity, type 2 diabetes, cardiovascular diseases, and certain types of cancer [12–14].

From a nutritional perspective, pulses are generally limiting in sulfur-containing amino acids (methionine and cysteine) and tryptophan, while providing relatively high amounts of lysine [15]; thus, combining different pulse crops as ingredients has been reported as an effective strategy to improve the nutritional profile of plant-based foods. Resourcefully, one of the most versatile ways to incorporate pulses into food products is to convert them into flour, as they can be readily used in bread, bakery products, and pasta that are regularly consumed worldwide while maintaining desirable technological performance during processing [11]. Nevertheless, pulse-based ingredients still present important amino acid profiles and sensory limitations that may restrict their use in food formulations.

In this context, microalgae, especially *Spirulina* (genus *Limnospira*), have emerged as a potential complement to protein sources. Unlike most pulses, *Spirulina* provides all essential amino acids, including methionine, together with highly digestible protein, making it a suitable complementary protein source to pulse composite flours. *Spirulina* biomass contains 50–70% protein (dry weight). It is also a source of vitamins, minerals, and bioactive compounds such as C-phycoerythrin (C-PC), carotenoids, and phenolic compounds, which are associated with potential health benefits [16]. Because of these features, *Spirulina* has attracted growing interest as an ingredient for food enrichment, especially in formulations aimed at improving nutritional quality and supporting the development of healthier [17,18] and sustainable food products due to the bioeconomy that integrates food, agriculture, pharmaceutical, electricity, and climate change fields [19].

Therefore, using microalgal biomass is a key strategy for biomass valorization and promoting circular economy approaches in the food sector. Given the rising global demand for nutritious and sustainable protein sources, microalgae such as *Spirulina* are recognized as important contributors to future food systems, with potential applications that combine nutritional benefits, resource efficiency, and support for global food security [20,21].

Within this framework, this review aims to explore the role of microalgae as innovative protein sources in plant-based food systems, with emphasis on their structural, technofunctional, and processing characteristics. It also examines the potential of combining microalgae with pulse-based ingredients as a strategy to enhance nutritional quality and functional performance in food formulations. Despite the growing interest in both protein sources, important research gaps remain, including: (i) the limited number of studies on multi-component composite flour systems combining *Spirulina* and pulse ingredients; (ii) the insufficient understanding of protein–protein interactions and their effects on techno-functional properties in complex food matrices; (iii) the lack of targeted strategies to overcome sensory limitations, particularly off-flavors and color changes associated with microalgae incorporation; and (iv) the limited application of these combined systems in bakery and other flour-based products. By integrating current knowledge and addressing these

3. General Results: Framework Summary

Bibliometric mapping is a well-established tool in scientific trend analysis, allowing researchers to identify the intellectual structure of a research field and detect emerging technological bottlenecks. The comparative analysis of keyword co-occurrence (Figure 1a,b) reveals the coexistence of two distinct, yet highly complementary, routes aimed at circumventing historical dependence on animal-derived proteins. Figure 1a,b were created using VOSviewer (version 1.16.19, Leiden University, Leiden, The Netherlands). The sizes of the circles and labels directly correspond to their weight; that is, the more frequently a term appears, the larger the circles and labels will be. For the keywords “Microalgae” OR “protein” OR “food”, presented in Figure 1a, it is possible to observe that the most frequently cited keywords were microalgae, protein source, development, technology, and health. On the other hand, when considering the words from the search “pulse” OR “bean” OR “protein” (Figure 1b), we highlight the terms protein, bean, application, property, functionality, flour, chickpea, and demand.

The network analyses provided by bibliometric tools shed light on the differing stages of technological maturity and the scientific purposes of these alternative protein sources. While legumes continue to underpin today’s plant-based products through their versatile flours, microalgae represent the scientific innovation vector for tomorrow’s food systems, anchored in advanced biotechnology and the appeal of precision health. From this section, it is important to highlight that future work should prioritize overcoming the high energy costs associated with microalgal downstream processing and investigating consumer sensory acceptance of hybrid formulations, paving the way for a sustainable, viable, and nutritionally superior protein transition.

In addition, Figure 1c,d provide data on documents by country or territory and by area. The geographical distribution of the literature and the categorization of publications by subject areas further elucidate the global footprint and highly interdisciplinary nature of this scientific domain. China and Italy lead global scientific production in this field, followed by the United Kingdom and Brazil. This geographical spread highlights a robust research interest centered in East Asia, Southern and Western Europe, and South America, reflecting diverse regional motivations—ranging from China’s focus on large-scale biomass utilization to Italy’s culinary-driven interest in plant-based food innovation.

Complementing this geographical data, the distribution of subject areas (Figure 1d) underscores the highly interdisciplinary framework required to advance alternative protein research. Agricultural and Biological Sciences represents the largest share at 15.2%, reflecting the fundamental need to understand raw material cultivation, crop physiology, and biomass yields. Engineering is the second-largest field at 11.7%, which directly correlates with a focus on downstream processing, extrusion, and extraction scale-up technologies. Biochemistry, Genetics and Molecular Biology (9.5%) and Chemistry (9.5%) collectively emphasize the molecular characterization, protein profiling, and chemical modifications required to improve nutritional value and structural integrity. The remaining literature is distributed across Physics and Astronomy (8.8%), Medicine (8%), Environmental Science (7.2%), Chemical Engineering (5.1%), and Materials Science (5.1%).

This diverse academic profile demonstrates that resolving the challenges of the alternative protein transition—such as texture-mimicking, allergen reduction, and environmental sustainability—requires a coordinated effort spanning basic molecular biology, food materials structuring, clinical health evaluation, and green process engineering.

4. Current Food Systems and Their Transition to Greater Sustainability

Current food systems, marked by the increasing reliance on animal-derived products, contribute to adverse health and environmental outcomes. At the same time, climate

change further threatens food security, underscoring the need for more sustainable protein sources [10,22]. Along these lines, growing interest in plant-based diets has increased the demand for sustainable alternative protein sources. Although soy has traditionally dominated this market because of its high protein content, mild flavor, and technofunctional properties, concerns regarding allergens, antinutritional factors, Genetically Modified Organisms (GMOs), and its extensive use as animal feed have stimulated interest in alternative protein sources [22–24]. As an alternative to soy, pulses have gained attention due to their high nutritional value and environmental benefits, including low water requirements, accounting for only 9.61% of the water needed for beef protein production; enhanced biodiversity; and biological nitrogen fixation, which reduces dependence on synthetic fertilizers and associated greenhouse gas emissions (GHGs) (Figure 2) [25].

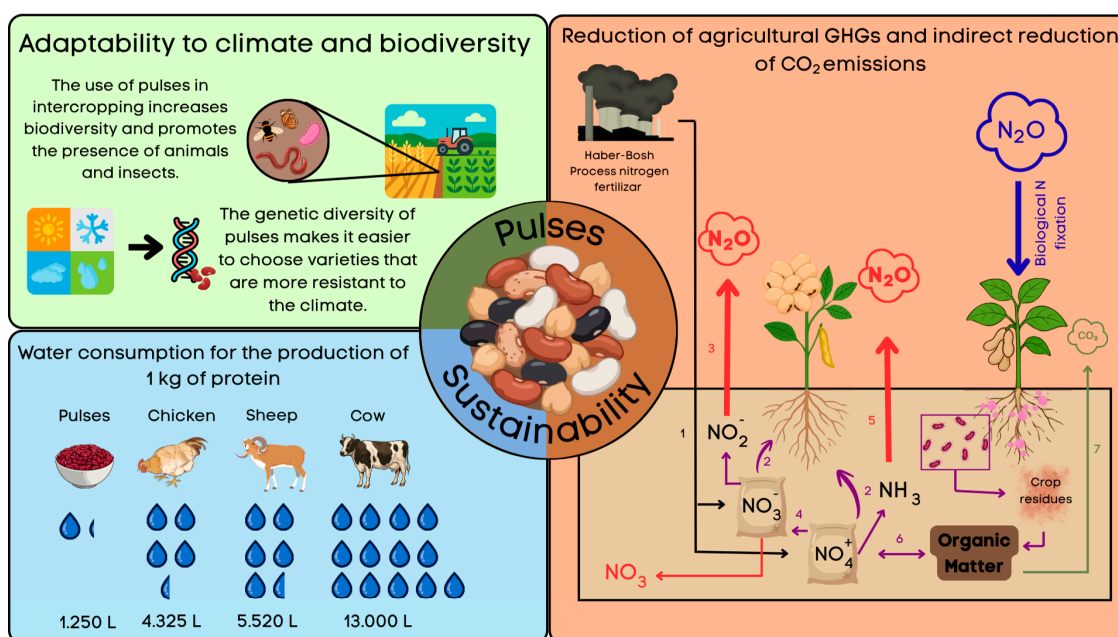


Figure 2. Schematic representation of the main environmental benefits of pulses, including water-use efficiency, biological nitrogen fixation, biodiversity conservation, and reduced greenhouse gas emissions.

The transition towards a more sustainable food system encompasses resource-efficient production, carbon capture through photosynthesis, and circular production approaches, including cultivation in nutrient-rich wastewater while supporting several Sustainable Development Goals (SDGs). Microalgae, for instance (Figure 3), adapt to extreme conditions, allowing cultivation in high-temperature environments and in wastewater because they grow better in alkaline media, which also promotes water treatment by effectively removing nutrients, especially nitrogen and phosphorus, and lowering biochemical oxygen demand, thus helping to close the production loop [26].

As illustrated in Figures 2 and 3, pulses and *Spirulina* offer complementary sustainability advantages compared with conventional animal protein production [26,27], supporting several SDGs, particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production).

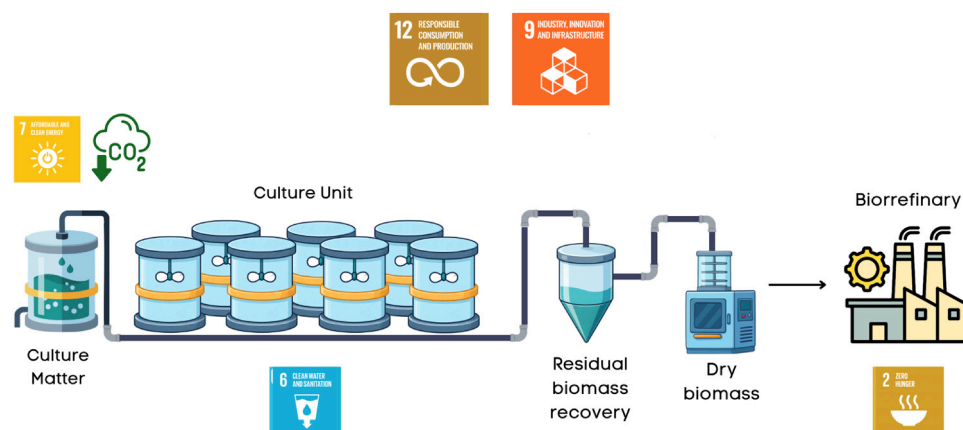


Figure 3. Circular biorefinery approach for Spirulina production and its contribution to the Sustainable Development Goals (SDGs).

5. Nutritional Characteristics and Processing of Pulses

Pulses are legumes harvested exclusively for their whole dried grains, excluding those used for oil extraction or other plant parts such as pods [11,28–30]. They offer several nutritional and health benefits common to many dried grain varieties [11,28,29] and have a higher protein content (usually ranging from about 15 to 30% by dry weight) than cereals like wheat, corn, and oats, which contain an average of 12.5% protein [11]. Additionally, pulses are important sources of minerals, dietary fiber, vitamins, and bioactive compounds, making them suitable ingredients for nutrient-dense foods [11].

Among these bioactive compounds are alkaloids, oligosaccharides, polyphenolics, saponins, phytosteroids, gamma-aminobutyric acid (GABA), lectins, phytic acid, tannins, and trypsin and chymotrypsin inhibitors, which have been linked to both health-promoting properties and antinutritional effects [28]. Conventional processing typically involves hydrating the seeds, either by soaking them in water at room temperature or higher temperatures or by blanching, followed by thermal cooking steps that soften the grains and make them suitable for consumption. During soaking and other aqueous pretreatments, water-soluble compounds such as simple sugars, oligosaccharides, vitamins, minerals, and polyphenols may be partially lost through leaching. However, hydration and heating promote starch gelatinization, solubilize pectin, and denature proteins, thereby altering the beans' technological and functional properties [11]. After hydration and cooking, pulses tend to undergo cellular separation and structural softening, resulting in improved texture and palatability [11,31,32].

Treatments such as milling, fermentation, and germination are often used to reduce antinutritional compounds like trypsin inhibitors, tannins, and phytic acid [11,28,33]. Germination and fermentation are among the most effective bioprocessing strategies for improving the nutritional quality of pulses. Germination activates endogenous enzymes, including phytases, proteases, and α -galactosidases, which degrade phytic acid, protease inhibitors, and raffinose-family oligosaccharides, thereby enhancing mineral bioavailability and protein digestibility [34,35]. Mali and Kumar [36] observed lower trypsin inhibitor activity, tannin content, and phytic acid levels in germinated black beans than in raw black beans.

Additionally, fermentation further promotes the microbial degradation of antinutritional compounds by producing phytases and proteolytic enzymes, while also increasing the release of bioactive compounds and antioxidant activity [34]. Interestingly, some compounds traditionally considered antinutritional, like saponins, tannins, and phytic acid, also exhibit beneficial properties. Saponins, tannins, and phytic acid exhibit antioxidant

activity [37], and trypsin inhibitors, raffinose, and phytic acid are associated with reduced cancer risk [33,38,39].

Moreover, the nutritional and functional properties of pulses vary considerably depending on their physical form, including whole seeds, pulse flours, and isolated carbohydrate, protein, or fiber fractions. For example, whole pulses with intact cotyledon cell walls are associated with a lower glycemic response but reduced iron bioavailability and folate accessibility. In contrast, milling disrupts the cotyledon cell walls, producing pulse flours with increased starch digestibility, higher glycemic response, and improved iron bioavailability and folate content [11]. Among pulse crops, beans deserve particular attention for their global production, nutritional quality, versatility, and extensive use as food ingredients.

Beans: Proteins, Techno-Functional, and Application Aspects

Among pulses, beans are prominent staple foods in many cultures. Global production of dried beans has remained steady from 2020 to 2024, averaging over 29 million tons annually [40]. Table 1 summarizes protein content in bean flours reported in the literature, providing an overview of values ranging from 8.19 to 23%. In terms of protein quality, beans contain several essential amino acids, with methionine and cysteine identified as the limiting amino acids, while still providing lysine, which is limiting in cereals [30,33].

Table 1. Protein content of selected bean flours reported in the literature.

Bean Flour	Protein (%)	Reference
Black bean flour (germinated)	12.68	[41]
Kidney bean flour (germinated)	12.15	[41]
Mung bean flour (germinated)	13.56	[41]
Red bean flour (germinated)	11.92	[41]
Red bean flour	8.19	[42]
White bean flour	23.0	[43]
White bean flour	18.77	[44]

Due to their nutritional quality, cost, flavor, and cultural aspects, beans and their components have not only been among the most widely consumed grains but also have been widely studied for their significant potential as ingredients in the food industry and for innovative technological applications. They are used in the development of edible films for packaging [45,46] and as food ingredients in prepared foods, seasonings, and plant-based products such as meat analogs, egg analogs, and dairy substitutes. Additionally, bean flour is used in flour-based products such as cookies, snacks, cakes, and noodles [11,47]. Regarding the extraction of protein isolates and concentrates, considerable progress has been made using both chemical methods—such as glycation, acylation, succinylation, and phosphorylation—and physical strategies—such as microwave heating, ultrasound treatment, cold plasma treatment, and ultrafiltration. Biological and enzymatic modifications are also employed to produce bean proteins [47,48].

Bean flours, protein isolates, and protein concentrates have technological properties that influence the quality of products made with these ingredients, including solubility, water- and oil-holding capacities (WHC, OHC, respectively), emulsifying and foaming abilities, thermal stability, and gel-forming capacity [47,49]. Compared with wheat flour, bean flours often exhibit higher WHC, solubility, emulsifying ability, and foaming properties. These factors affect bread characteristics such as volume, color, springiness, hardness, resistance, and texture [33]. Exploring additional technological and functional associations with complementary ingredients may also yield promising benefits, such as nutritional synergy between Spirulina and beans.

6. Spirulina as a Food Ingredient

Microalgae are a highly diverse group of unicellular or multicellular, photosynthetic microorganisms that can be either eukaryotic or prokaryotic, found in freshwater, marine, and terrestrial environments. They grow relatively quickly compared to land plants and have efficient photosynthetic processes, allowing microalgae to produce large amounts of biomolecules such as proteins, lipids, vitamins, pigments, and minerals [50], thereby increasing interest in their use as sustainable food ingredients [16,51]. Among the species studied for nutritional purposes, Spirulina [52] has been recognized as GRAS (Generally Recognized as Safe) by the Food and Drug Administration (FDA) [53], and its safety as a dietary supplement has been confirmed by the United States Pharmacopeia [54]. Spirulina is especially notable for its nutritional profile, which includes approximately 57.5% protein, 23.9% carbohydrate, and 7.72% fat [55].

Additionally, it contains all essential amino acids [56], vitamins such as α -tocopherol, β -carotene, B-complex, vitamin K1, and minerals like magnesium (Mg), phosphorus (P), iron (Fe), calcium (Ca), copper (Cu), and selenium (Se), among others, within a nutritionally accessible food matrix [16,51,57], making it especially appealing for vegetarian and plant-based food models. Spirulina also provides the high-value protein pigment C-phycocyanin (C-PC), which offers potential health benefits due to its antioxidant activity [58], supports neuro- and hepatoprotective pathways [59–61], and acts as an anti-obesity agent while improving reproductive health in mice [62–64]. Microalgae contain phenolic compounds, chlorophylls, carotenoids, and peptides as bioactive compounds [65,66], with pigments such as chlorophylls and carotenoids serving as natural coloring agents and possessing antioxidant properties [67,68].

Furthermore, other technofunctional properties of Spirulina, such as WHC, OHC, foaming ability, solubility, emulsion-stabilizing capacity, viscoelasticity, and structuring, have been documented in the scientific literature [69,70]. These functional properties depend on processing methods, pH levels, and whether Spirulina is fresh or dehydrated [71]. They also rely on the composition of polysaccharides and lipids, as well as the amphiphilic nature of proteins, which influence hydration, dispersion, interfacial stabilization, and texture formation [52,72,73]. For example, a protein solubility of $50.75\% \pm 0.95$ was achieved through high-pressure homogenization (HPH) at 500 bars [74], while ultrasound-based extracts from defatted Spirulina biomass showed approximately 95% solubility across a pH range of 5–9 [71]. High-shear homogenization (HSH) and HPH treatments released polysaccharides and proteins from Spirulina at 4–5 wt.%, creating aggregates that filled soy protein isolate hydrogels and improved gel strength, chewiness, and hardness [75].

The solubility of Spirulina protein [76] and the rapid dispersibility of the entire biomass support its use as an ingredient, such as in flours, to create desirable textural characteristics for technological applications, as it acts as a natural texturizing additive suitable for clean-label and nutritional enhancement purposes [52,72,73]. Regarding bakery products (Table 2) that use flour as an ingredient, most studies have employed wheat flour or developed gluten-free baked goods with rice or quinoa flour. In contrast, pulse flours and multi-component flours combined with Spirulina remain underexplored [77]. In addition to providing a nutritional boost in protein and fiber and enriching the diet with minerals [78,79], color contribution was also reported [79,80], and all these studies noted improved antioxidant activity associated with Spirulina incorporation.

Among other technofunctional properties, no differences were observed in dough rheology for Spirulina and its recovered biomass after C-PC extraction at 3%, even with pH shifts [81], which is a promising result for breadmaking, showing increased specific volume and stable crumb moisture, baking loss, water activity, and firmness over 48 h. In crackers with 1.5% and 2.5% Spirulina, hardness improved, whereas in grissini with 1.5%, 2.5%, and

3.5% Spirulina, hardness also increased. Thus, low-to-moderate inclusion levels (typically 2–3%) preserved dough rheology by maintaining dough development time and stability (Table 2). Conversely, in muffins with 4% Spirulina, hardness, gumminess, and chewiness were reduced [82]. At 5, 10, and 15% Spirulina, hardness in gluten-free crackers decreased, while dough extensibility and resistance increased [83]. Thus, different behaviors in Spirulina's technofunctional properties are observed depending on concentration, ingredient interactions within the food matrix, and processing techniques; for example, thermal and HSH treatments were more effective in dissolving polysaccharides, while HPH enhanced protein dissolution [75].

Table 2. Comparative overview of Spirulina's technofunctional potential in bakery products and baking system ingredients published in the last five years.

Food Category	Composition	Technofunctional Properties	Antioxidant Activity	Reference
Bread				
Bread (whole wheat flour based)	Spirulina at 1, 5 and 10%	Spirulina at 10% improved protein content, and all the studied concentrations enhanced fiber content. At 5 and 10%, the protein digestibility and availability were superior.	-	[78]
Bread (wheat flour based)	Spirulina whole biomass or recovered Spirulina biomass after C-PC extraction (RB) at 3%	Spirulina whole biomass and its fraction did not affect the degree of softening (mN/m) of the doughs nor the development time (min). The dough stability (min) was higher in SB samples, which resulted in a positive effect on the physical profile of the breads. At 3%, neither Spirulina nor RB interfered with the rheological parameters of the doughs. The pH increased (5.63 ± 0.05 in Spirulina; 5.70 ± 0.05 in RB and 5.42 ± 0.05 in control). The specific volume (cm^3/g) increased with both samples, but no statistically significant differences were observed in crumb moisture, bake loss, or water activity of the breads. Firmness from 0 to 48 h did not present statistical changes. Cohesiveness of the samples containing Spirulina reduced after 48 h. Protein digestibility, constant at approximately 80%, was achieved in all the samples.	¹ DPPH ($\mu\text{M}^2 \text{ TE/g}$) of 36.32 ± 0.04 for Spirulina samples and of 34.91 ± 0.09 for RB was statistically superior ($p < 0.05$) to the control (3.28 ± 0.01). The same trend ($p < 0.05$) was observed in ³ FRAP ($\mu\text{M TE/g}$) (7.49 ± 0.10 ; 7.38 ± 0.19 ; 2.06 ± 0.02 , respectively).	[81]
Bread (semi-whole wheat flour based)	Spirulina at 1 and 2%	Spirulina did not affect the rheological parameters up to 2%. Spirulina improved ash and protein contents in bread. Dough extensibility (mm) was lower in Spirulina at 2% samples but did not change at 1% compared to the control, while dough tenacity (mm) was enhanced dose-dependently. WAC of 1.87 ± 0.01 ; 1.81 ± 0.03 and 1.79 ± 0.02 was observed for Spirulina at 2%, 1% and control, with statistically significant difference in Spirulina at 2%.	-	[27]
Bread (wheat flour based)	Spirulina at 1, 2.5 and 4%	Dough stability has improved at 1% and decreased at 4% enriched samples. Specific volume (mL/g) was higher at 1% (2.93 ± 0.01) compared to the control (2.83 ± 0.01), whereas porosity (%) was higher at 2.5% enriched samples.	-	[84]

Table 2. Cont.

Food Category	Composition	Technofunctional Properties	Antioxidant Activity	Reference
Baguette (wheat flour based)	Spirulina at 1.8 to 4.18% and whey protein at 9 to 21%	Spirulina up to 3% increased WAC. The highest dough stability was achieved with Spirulina at 1.8%. Spirulina contributed to the bread firmness more than whey protein. Cohesiveness and resilience were temperature dependent.	-	[85]
Muffins				
Muffin (wheat flour based)	Spirulina at 4%	Spirulina improved protein and ash content and reduced fat. Reduced glycemic index was observed. Spirulina reduced hardness, gumminess and chewiness.	⁴ TPC (mg ⁵ GAE/100 g) was 20.20 ± 0.35 ($p < 0.05$) when compared to the control (18.42 ± 0.06); same behavior ($p < 0.05$) was observed for DPPH (mM TE/100 g) (0.053 ± 0.00 versus 0.018 ± 0.00) and ⁶ ABTS (mM TE/100 g) (0.163 ± 0.00 versus 0.126 ± 0.00). Thus, Spirulina has led to statistically significantly greater antioxidant activity.	[82]
Muffin (wheat flour based)	Spirulina at 1, 3 and 6%	Spirulina incorporation did not affect the pH of the doughs. The highest volume (cm ³) was achieved at 1% Spirulina concentration (216.67 ± 5.77). Ash content increased as Spirulina increased.	-	[73]
Snacks				
Biscuits and snacks gluten free (quinoa flour based)	Spirulina at 3, 6 and 9%	Spirulina in all concentrations improved protein, fat, ash, and fiber contents in biscuits. Thickness and spread ratio of the dough remained constant within different Spirulina concentrations, while the volume (cm ³) and specific volume (v/w) decreased from 15.33 to 9.33 and from 1.28 to 0.97 when comparing control to samples at 9% Spirulina concentration. The biscuits' hardness (N) was the most affected parameter in ⁷ TPA analysis (from 100.99 in control to 21.33 in Spirulina at 9%); however, for Spirulina at 3 and 6%, hardness was constant (100.92 and 99.67, respectively).	TPC (mg/g) and DPPH $\mu\text{mol/g}$ improved both for biscuits and snacks in a dose-dependent manner, achieving the highest ($p < 0.05$) values of TPC (3.25 ± 0.42 in biscuits; 2.90 ± 0.11 in snacks) and of DPPH ($p < 0.05$) (50.18 ± 0.20 in biscuits; 41.49 ± 0.15 in snacks) for Spirulina at 9%.	[79]
Biscuits (wheat flour based)	Spirulina at 1, 2.5 and 4%	Hardness (N) was superior in samples at the highest concentration. Protein and amino acid contents increased at the highest concentration.	-	[86]
Extruded snacks (corn grits based)	Spirulina or Spirulina hydrolysate or peptide fraction < 4 kDa or peptide fraction > 4 kDa at 2%	Moisture and protein were enhanced in samples containing peptide fraction < 4 kDa. Ash content did not change between all the samples. Fracturability (N) was improved in both peptide fraction incorporated samples but was higher in <4 kDa snacks. Hardness (N) was highest in <4 kDa snacks.	Snacks containing < 4 kDa peptides from Spirulina presented the highest ($p < 0.05$) ABTS activity ($7.45 \mu\text{mol TE/g}$).	[87]

Table 2. Cont.

Food Category	Composition	Technofunctional Properties	Antioxidant Activity	Reference
Rice crackers (Gluten free)	Spirulina at 5, 10 and 15%	Spirulina at 10 and 15% increased the viscoelastic parameter of the dough. The dough presented higher extensibility and resistance in all concentrations and decreased hardness compared to the control. Spirulina contributed to protein. Fiber and ash enhancement in all the studied concentrations.	DDPH ($\mu\text{mol TE}/100\text{ g}$) was superior ($p < 0.05$) in all the samples compared to the control (0.46 ± 0.04) and achieved the highest value at 15% (1.24 ± 0.07). The same trend ($p < 0.05$) was observed in ABTS ($\mu\text{mol TE}/100\text{ g}$) (6.23 ± 0.64) at 15% Spirulina versus control (2.47 ± 1.43).	[83]
Crackers and grissini (wheat flour based)	Spirulina at 1.5, 2.5 and 3.5%	Spirulina at 1.5% and 2.5% improved hardness (N) of crackers, and all the concentrations improved hardness (N) in grissini compared to the control.		[80]
Brown rice protein bar	Spirulina (0–2%) and C-PC (0–0.4%)	Spirulina at 2% and C-PC at 0.2% decreased adhesiveness but increased in higher concentrations. Springiness decreased at lower concentrations, and chewiness increased in concentrations of Spirulina up to 1%.	Spirulina at 2% and C-PC at 0.4% significantly improved ($p < 0.05$) polyphenols (mg GAE/g) and flavonoid content (mg QE/g), DPPH (%), and FRAP (mg AAE/g) antioxidant activities. The authors provided surface graphs and not numerical data.	[88]
Other				
Premix of tempeh flour	Spirulina at 1%	OAC decreased in heat-moisture treatment and did not change in annealing treatment. Same behavior was observed for WAC. Spirulina enhanced the flour's swelling volume. Both treatments have improved the flour's solubility.	Heat-moisture treatment and annealing treatment improved antioxidant activity ($p < 0.05$) (42.77 ± 0.00 ; 42.97 ± 0.00 in DPPH (%) analysis, respectively) compared to Spirulina tempeh flour without any treatment (20.40 ± 0.00).	[89]

¹ DPPH: 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; ² FRAP: Ferric Reducing Antioxidant Power; ³ TPC: Total phenolic compound; ⁴ GAE: Gallic acid equivalent; ⁵ TE: Trolox equivalent; ⁶ ABTS: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) assay; ⁷ TPA: Texture profile analysis.

Although nutritional and technofunctional benefits have been reported, making Spirulina an appealing ingredient for improving flours and bakery systems, the volatile compounds in Spirulina biomass can affect the flavor and aroma of the final products. Their amino acid composition contributes to umami and bitter tastes, which limit Spirulina's inclusion to 0.1–7% for better acceptability [90]. In this way, several strategies have been proposed to overcome these sensory limitations. Microencapsulation [91,92] masks undesirable odor and taste while protecting pigments and other bioactive compounds from degradation during processing, digestion and storage. Fermentation, particularly with lactic acid bacteria, promotes deodorization and proteolysis of Spirulina [93], reducing off-flavor while generating acetoin and creamy odor. Likewise, enzymatic pre- or post-processing regulates volatile compounds (VOCs), releasing flavor-active peptides and free amino acids, altering VOC precursors responsible for earthy and muddy odors, improving the sensory profile of Spirulina-enriched foods [94,95].

Additionally, using *Spirulina* extracts like C-PC [96] improves acceptability, but using whole biomass remains an underexplored approach; flavor pairing, such as with lemon-basil [97], enhances consumer preference. Formulations containing low to moderate *Spirulina* levels ($\leq 4\%$) displayed a VOCs profile dominated by terpenes, furans, and mild alcohols, such as limonene, furfural, and short-chain alcohols, when combined with sugar powder, cream fat, whey powder, lemon extract, stevia, milk powder and salt to form a fortified cream filler [98]. These VOCs are associated with desirable sweet and roasted aroma notes and contribute to the high sensory acceptability (89%) observed for these formulations. Accordingly, flavor pairing with curcumin mitigated the fishy odor imparted by *Spirulina* through competitive interactions with hexanal and 1-octen-3-ol, resulting in improved sensory acceptability in bread [99]. A feasible approach consists of integrating low-cost flavor pairing and fermentation with bean-based flours to address the technological challenge of sensory acceptance. In this context, developing premix flours offers efficient baking solutions for both household and industrial uses [100]. Their incorporation into widely consumed flour-based products, such as breads, cakes, and pasta, may further facilitate consumer acceptance, as these familiar food matrices are more likely to accommodate nutritional innovations.

7. Blended Flours: Concept, Applications, Technological and Functional Aspects

Composite flours are blends of two or more flours from cereals, legumes, tubers, nuts, or other sources [101,102]. Although their initial adoption was limited, growing consumer demand for nutritious, sustainable, and gluten-free products has renewed interest in composite flours as technofunctional food ingredients [101].

Numerous studies report the use of composite flours as ingredients in a wide range of food products, as shown in Table 3. For composite flours that include bean flour, recent research has shown their use in products such as bread [42,44,103,104], biscuits [105], cakes [106], muffins [41,43], snacks [107], and noodles [108]. Compared with traditional wheat-based formulations or rice-based gluten-free products, adding bean flour enhances nutritional properties, especially protein content [41,44,103–109] and dietary fiber [42,43,103,109,110]. Pulse flours, owing to their higher protein and dietary fiber contents, generally increase water absorption compared to products with higher starch content, especially when contrasted with wheat flour [111]. Currently, rice flour is the most widely used gluten-free flour, though it often results in less dough development. Studies combining rice flour with legume flours, such as chickpea flour, have demonstrated improved emulsifying properties and enhanced dough development [44,106,112,113].

From a technological perspective, Rajpurohit et al. [104] reported no significant changes in bread hardness or springiness when up to 10% of whole wheat flour was replaced with red or navy bean flour, and up to 5% with cowpea flour. However, higher replacement levels reduced dough strength and increased bread hardness. Cakir et al. [41], working with muffins made from composite flour of different beans, observed a higher specific volume compared to muffins made with rice flour and a softer crumb than wheat-flour muffins, although hardness increased with higher levels of germinated bean flour. For snacks made with mung bean composite flour, Bozdogan et al. [107] found that changes in mung bean flour content, feed moisture, and extruder barrel temperature significantly affected snack properties, including expansion ratio, hardness, crispiness, water solubility index, and extrudate morphology. Specifically, higher mung bean flour content, feed moisture, and barrel temperature decreased the expansion ratio and crispiness of the snacks. Therefore, creating a composite flour with microalgae may optimize texturization.

Table 3. Nutritional, sensory, and antioxidant characteristics of bean-based composite flours in bakery products published in the last two years.

Product Category	Composition	Protein Content	Sensory Evaluation	Antioxidant Activity and Antinutrient Content	Reference
Bread					
Bread (yeast-free and gluten-free)	White bean flour 15–30%, hazelnut flour 15–30%, white bean flour and hazelnut flour 15–30%.	The protein content was expressed as a (g/100 g). White bean flour (18.77 ± 0.02), hazelnut flour (15.60 ± 0.03), rice flour (5.87 ± 0.05), corn starch (0.60 ± 0.00).	Free choice profiling rapid sensory description method.	Antioxidant capacity and ¹ TPC of the breads were not evaluated. The total protein content (mg ² GAE/g) was evaluated in the flours.	[44]
Bread	Germinated mung bean flour, germinated white kidney bean flour, germinated brown rice flour (1:1:1).	Bread containing 25% composite flour showed significantly higher protein content.	The samples were evaluated using a ³ HE ($n = 30$, scale: 9-point). The control bread showed no significant difference compared with bread containing 25% blended flour.	The bread containing 25% blended flour presented higher TPC (mg GAE/g) and ⁴ GABA mg/100 g ($p < 0.05$) than the control bread.	[103]
Bagel	Red bean flour at 5%, 10%, 15%, 20%	The red bean flour sample had a higher protein value than durum wheat semolina.	The 100% durum wheat semolina control sample showed a higher overall acceptability score than the sample with 20% red kidney bean flour.	-	[42]
Muffin and cake					
Muffin	White bean flour/wheat flour/quinoa flour at: 25%/50%/25%;	The wheat flour control muffin showed a protein content of the optimized muffin containing wheat, white bean and quinoa flour a significant increase.	The samples were evaluated using a HE. The optimized muffin achieved an acceptability index of 71%.	The TPC of the optimized muffin was significantly higher than the control and no significant differences were observed in ⁵ DPPH antioxidant activity.	[43]
Muffin	Haricot bean, kidney bean, black bean, mung bean, or red bean at 20%	All formulations had higher protein values than the control.	The control showed the highest overall acceptability without significant differences compared with muffins containing sprouted haricot bean flour and sprouted black bean flour.	The muffin containing sprouted mung bean flour showed the highest TPC and the highest DPPH (%) and ABTS.	[41]

Table 3. Cont.

Product Category	Composition	Protein Content	Sensory Evaluation	Antioxidant Activity and Antinutrient Content	Reference
Cake (Gluten-free)	Sprouted mung bean flour, plantago mucilage, grape syrup and ⁶ DATEM emulsifier.	An increase in protein content with the incorporation of sprouted mung bean flour into the formulation.	The samples were evaluated by HE ($n = 10$, scale: 1–5) and the optimized cake showed greater overall acceptance.	Antioxidant activity, as assessed by DPPH activity (%) increased significantly in the optimized cake.	[106]
Snacks					
Dry choux pastry	Mung bean flour at 25%, 50%, and 75%	The protein content increased progressively with the increase in mung bean flour.	The highest overall acceptability was obtained in the 25% mung bean flour sample.	A dependent increase in ⁷ VC was observed, except in the 25% flour (lower than the control formulation.)	[109]
Dry choux pastry	Mung bean flour at 25%, 50%, and 75%	Control formulation (8.5 ± 0.3), 25% mung bean flour (12.3 ± 0.4), 50% mung bean flour (15.6 ± 0.5), 75% mung bean flour (18.7 ± 0.6)	Hedonic evaluation ($n = 32$, scale: 1–9): 25% mung bean flour (7.6 ± 0.9), 50% mung bean flour (6.8 ± 1.0), and 75% mung bean flour (6.2 ± 1.1).	Vitamin C content (mg/100 g): control formulation (56.48), 25% mung bean flour (47.06), 50% mung bean flour (94.13), and 75% mung bean flour (103.48).	[109]
Biscuits	Red bean flour at 25%, 50%, 75% and 100%	The samples with the highest proportion of malted bean flour exhibited the highest protein content.	Scores for all sensory attributes were evaluated by HE and decreased significantly with the incorporation of Red bean flour	Oxalate and phytate levels were similar in the biscuits from the different formulations. TPC increased in a concentration-dependent way.	[105]
Snacks	Mung bean flour 20%, 60%.	From 3.29% to 17.62%	Snacks containing 40% mung bean flour had greater overall accessibility.	-	[107]
Pasta					
Instant noodles	Common bean flour (CBF) at 5%, 10%, 15%, 30%.	The samples with the highest proportion of CBF exhibited the highest protein content.	-	The air-heat noodles exhibited a higher antioxidant activity than the frying noodles.	[108]

¹ TPC: Total phenolic compound; ² GAE: Gallic acid equivalent; ³ HE: Hedonic evaluation; ⁴ GABA: Gamma-aminobutyric acid; ⁵ DPPH: 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; ⁶ DATEM: Diacetyl tartaric acid esters of mono- and diglycerides; ⁷ VC: Vitamin C equivalent.

Sensory analysis of products made with bean composite flours generally shows better consumer acceptance when moderate amounts of bean flour are included. Some studies report higher overall acceptability compared with control formulations. Rajpurohit et al. [104] observed higher acceptability in bread containing 5% navy bean flour, and similar results were reported by Ruzana et al. [42] for bagels with 5% red bean flour. Cakir et al. [41] found higher acceptability of muffins than of a gluten-free, rice-flour-based control. Allahyari et al. [106], working with an optimized cake formula that includes germinated mung bean flour, plantago mucilage, grape syrup, and DATEM (an emulsifier found to improve the specific volume of gluten-free cakes), along with Bozdogan et al. [107],

who created snacks with 40% mung bean flour and optimized extrusion parameters, also achieved higher overall acceptability than the control formulations. To improve sensory acceptance of bean flour-based foods, reducing off-flavors such as beany, earthy, or green notes is essential. This highlights the need to balance nutritional benefits with sensory appeal to develop products with commercial value and foster positive perceptions of their consumption.

8. Protein Synergy and Nutritional Quality

Beans contain significant amounts of essential amino acids, though sulfur-containing amino acids and tryptophan are often considered limiting. However, they are rich in lysine, which is usually limited in cereals [30,33]. In the Food and Agriculture Organization of the United Nations (FAO) technical publication, Rawal and Navarro [30] compiled data on Protein Digestibility-Corrected Amino Acid Scores (PDCAAS) of pulses and foods. Some PDCAAS values listed include 0.68 for kidney beans, 0.53 for black beans, and 0.70 for navy beans, compared to 1.00 for egg white and 0.92 for beef. According to the FAO/INFOODS global food composition database for pulses [114], the amino acid content of common beans per 100 g includes alanine 971 mg, arginine 1270 mg, aspartic acid 2520 mg, cysteine 104 mg, glutamic acid 3380 mg, glycine 898 mg, histidine 590 mg, isoleucine 760 mg, leucine 1480 mg, lysine 1300 mg, methionine 185 mg, phenylalanine 1000 mg, proline 921 mg, serine 1220 mg, threonine 881 mg, tyrosine 638 mg, valine 961 mg [33,114], tryptophan 610 mg [113]. Franczyk et al. [115] reported amino acid scores (AAS) ranging from 0.76 to 0.88 and in vitro protein digestibility of 72.69% to 73.99% for navy beans subjected to different pretreatments, identifying methionine and cysteine as limiting amino acids. Senthilkumar et al. [116] reported an in vitro protein digestibility of $82.78 \pm 0.26\%$ for cooked red kidney bean protein isolate, higher than the value observed for raw red kidney bean protein isolate ($77.17 \pm 0.19\%$).

Given the amino acid profile of beans, combining beans with Spirulina, a superfood due to its complete amino acid profile and high protein content [57], may help address these limitations and enhance the nutritional and functional quality of newly developed products. The amino acid profile is crucial for assessing nutritional quality [117]. The amino acid composition in Spirulina powder included (g/100 g) all essential amino acids: isoleucine (2.16 ± 0.13); leucine (6.14 ± 0.48); lysine (6.27 ± 0.45); methionine (1.56 ± 0.06); phenylalanine (3.35 ± 0.27); threonine (4.25 ± 0.23); tryptophan (0.04 ± 0.00); valine (3.64 ± 0.14), besides the non-essential, such as cysteine (0.13 ± 0.00) and tyrosine (2.07 ± 0.13) [118].

This composition, along with protein content, lipid profile, vitamin levels, pigment content, and mineral levels, varies with cultivation method. Still, Spirulina is a valuable source for enhancing the nutritional quality of food matrices. For example, when added at 4% to muffins containing wheat flour, milk, eggs, rapeseed oil, sugar, and baking powder, it significantly increased the levels of essential amino acids (mg/g protein): isoleucine (4.03 ± 0.05); leucine (7.93 ± 0.1); lysine (4.16 ± 0.11); methionine (4.59 ± 0.08); phenylalanine (4.98 ± 0.09); threonine (3.59 ± 0.1); and valine (4.93 ± 0.14) [82]. It also raised protein and ash content while lowering fat content, with no notable changes in carbohydrate and moisture levels. Other non-essential amino acids significantly contributed by Spirulina at 4% included cysteine, tyrosine, histidine, aspartic acid, serine, glycine, alanine, and arginine. No significant differences were observed in glutamic acid and proline with Spirulina enrichment. According to the protein quality score (%), lysine was the limiting amino acid in the final product [82]. Among the essential amino acids in crackers containing wheat flour, water, yeast, salt, baking powder, and Spirulina at 1.5%, levels of isoleucine, leucine, lysine, tryptophan, and valine were observed, with lysine showing the lowest value (0.1 mg/100 g). In both products, protein synergy between Spirulina and pulse flours

can improve lysine content, since the high lysine and folate levels in pulses make them particularly suitable for inclusion in composite flours with cereals [119].

Therefore, to illustrate the potential nutritional complementarity between these protein sources, a theoretical amino acid composition was estimated for a formulation containing 25% common bean flour (20.9% protein [33]) and 5% *Spirulina* (57.5% protein [55]), based on amino acid composition data reported in the literature [33,118]. As shown in Table 4, the contribution of each ingredient to the indispensable amino acid profile was calculated and subsequently expressed as amino acid content/g of protein, following the FAO reference pattern for protein quality assessment [120]. AAS were then estimated by comparing the theoretical protein blend with the FAO amino acid scoring pattern for children > 3 years, adolescents, and adults. Hence, to estimate the theoretical PDCAAS, an overall protein digestibility of 80% was assumed for the protein blend, according to the literature for *Spirulina* [121] and pulses [116].

When the amino acid profile of the protein blend was compared with the FAO reference pattern, sulfur-containing amino acids (methionine + cysteine) remained the first-limiting amino acid group (0.84 AAS), although their content was substantially improved compared with bean protein alone and comparable to the range reported for navy beans (0.76–0.88) [115]. In addition, assuming an overall protein digestibility of 80%, the PDCAAS of the blend was estimated at 0.67, a moderate protein quality. Nevertheless, these values represent theoretical estimates derived from literature composition data and should be validated experimentally through amino acid analysis and digestibility measurements of the final formulation. Future research should also investigate composite flours incorporating *Spirulina*, beans, and cereals or pseudocereals to optimize amino acid complementarity, protein quality, and improve the technological and sensory performance of bakery products.

Table 4. Theoretical amino acid composition of a formulation containing 25% common bean flour and 5% *Spirulina*, expressed per 100 g of product and per gram of protein.

Amino Acid	Bean Flour at 25% (mg)	Spirulina at 5% (mg)	Total (mg/100 g Product)	Protein Blend (mg/g Protein)	FAO Report (mg/g Protein)	AAS
Cysteine	26.00	6.50	32.50	4.01	-	-
Isoleucine	190.00	108.00	298.00	36.79	30	1.23
Leucine	370.00	307.00	677.00	83.58	61	1.37
Lysine	325.00	313.50	638.50	78.83	48	1.64
Methionine	46.25	78.00	124.25	15.34	-	-
Methionine + cysteine	72.25	84.50	156.75	19.35	23	0.84
Phenylalanine	250.00	167.50	417.50	51.54	-	-
Threonine	220.25	212.50	432.75	53.43	25	2.14
Tryptophan	152.50	2.00	154.50	19.07	6.6	2.89
Tyrosine	159.50	103.50	263.00	32.47	-	-
Phenylalanine + tyrosine	409.50	271.00	680.50	84.01	41	2.05
Valine	240.25	182.00	422.25	52.13	40	1.30

AAS: amino acid score.

Although the antioxidant and anti-inflammatory properties of pulses and *Spirulina* have been investigated individually [12–14,122] in the prevention of chronic diseases, studies evaluating their combined effects remain limited. Their combination may offer complementary mechanisms by broadening the spectrum of bioactive compounds and enhancing protection against oxidative stress and inflammation, by scavenging reactive oxygen species and chelating pro-oxidant metals [81]. However, current evidence is largely indirect, and future studies should investigate whether pulse–*Spirulina* formulations produce additive or synergistic functional effects using in vitro, in vivo, and clinical approaches.

9. Bioactive Properties and Functional Potential

Several studies report health benefits associated with bean consumption, including reduced risks of coronary heart disease, cardiovascular disease, certain cancers, and diabetes [123]. Recent research by Roytrakul et al. [124] isolated peptides from red beans that demonstrate anticancer, antioxidant, and antihypertensive effects. Eckhof et al. [125] identified activation of peroxisome proliferator-activated receptor γ in two common bean landraces, which is related to the regulation of energy balance and metabolic functions. Vieira et al. [126] studied how eating bean flour affects gut microbiota and cardiac remodeling after myocardial infarction in male Wistar rats, noting only changes in gut microbiota in this model.

10]The bioactive compounds and antioxidant levels in bean flour have been extensively studied, particularly examining how processing methods such as cooking, germination, and fermentation, as well as various food uses, affect these properties. Cakir et al. [41] found that muffins made with germinated bean flour exhibited higher antioxidant activity than those made with wheat or rice flour. A muffin with 20% mung bean flour had a total phenolic content of 3.09 ± 0.04 (gallic acid equivalent/g), and the DPPH inhibition was 27.06% for muffins with 20% black bean flour and 50.25% for those with 20% mung bean flour. These muffins also exhibited higher ABTS activity and flavonoid content. Akawus et al. [105] observed significant differences in total phenolic content in biscuits made with germinated red bean flour, reporting values of 5.52 ± 0.64 (gallic acid equivalent/g) for biscuits made with 100% wheat flour and 25.01 ± 1.23 (gallic acid equivalent/g) for biscuits made with 100% red bean flour. Bassett et al. [43] reported total phenolic contents of 33 (gallic acid equivalent/g) in muffins made with 100% wheat flour and 110 (gallic acid equivalent/g) in muffins made with a mixed flour containing 25% white bean flour, 50% wheat flour, and 25% quinoa flour. Loikaeo [103] analyzed gamma-aminobutyric acid (GABA) content in a mixed flour made from germinated mung bean flour, germinated white kidney bean flour, and germinated brown rice flour (1:1:1), recording 19.53 ± 0.16 (mg/100 g), compared to 1.97 ± 0.01 (mg/100 g) in wheat flour. The GABA content in bread made with 25% of this mixed flour reached 79.47 ± 0.02 (mg/100 g).

When added to foods, Spirulina provides both protein and bioactive compounds linked to antioxidant, anti-inflammatory, neuroprotective, and anticancer effects. Carotenoids, C-phycocyanin, chlorophyll, and vitamins are among the main compounds responsible for these benefits [3,5,127,128]. The combination of beans and Spirulina shows strong potential for the development of new ingredients and functional food applications. Such formulations can create nutritionally dense products with antioxidant properties and potential health benefits, while also appealing to consumers seeking clean-label options made from whole, natural ingredients.

10. Market Trends, Innovation, and Conclusions

The global plant-based food market has experienced significant expansion over the past decade, although recent reports indicate a phase of adjustment and market maturation in certain regions. While early growth was particularly strong in North America and Europe, where plant-based products achieved higher market penetration, more recent trends suggest stabilization or even decline in some product categories, driven by factors such as pricing, sensory expectations, and consumer skepticism [9,129]. Emerging markets across Asia and Latin America continue to show growth potential, although expansion remains heterogeneous and shaped by factors such as affordability, consumer perceptions, and local market dynamics [2,130]. These dynamics indicate that the “hype”

phase of alternative proteins is transitioning into a more competitive and structured market environment.

Diversification of plant-based ingredients is no longer optional; it is essential to meet both nutritional requirements and organoleptic consumer expectations. Pulses, particularly beans, are already well-established in the market due to their affordability, availability, and nutritional value. However, their application in food systems still faces technological and sensory challenges, including off-flavors, suboptimal functionality in certain matrices, and imbalanced amino acid profiles [11–13]. Microalgae, such as *Spirulina*, have gained attention as high-value functional ingredients, supported by their rich protein content, complete amino acid profile, and bioactive potential [4,51,131]. Despite this, their large-scale incorporation into food products is still constrained by sensory limitations, cost, and processing challenges [90,95].

Current market and research trends indicate a shift toward clean-label, nutrient-dense, and multifunctional ingredients, as well as the development of composite and premix flours tailored for both industrial and household applications [100,111,132]. Furthermore, microalgae have been identified as key components in the emerging bioeconomy, contributing to sustainable production systems and circular resource use [20,21,26]. The challenge, therefore, lies in developing formulations that combine nutritional quality, technological performance, and environmental sustainability in a single system.

The convergence of these trends has encouraged the exploration of multi-ingredient systems designed to enhance both product performance and nutritional value. The synergy between pulse and microalgal biomass, such as *Spirulina*, represents a promising frontier, enabling improved amino acid balance. However, the proposed theoretical amino acid composition still has methionine-cysteine-limiting amino acids (AAS of 0.84) in a hypothesized food product containing composite flour of 25% common bean flour and 5% *Spirulina* powder, where the PDCAA was 0.67 considering a protein digestibility of 80%. However, when applied to complex food matrices with other ingredients such as cereal or pseudocereal flours, the methionine-cysteine AAS may be enhanced. In addition, composite flours based on pulses and *Spirulina* may enhance protein content and incorporate bioactive compounds into food formulations. Such combinations may also influence key technological properties, including water absorption, emulsification, and textural behavior, which are critical for the development of bakery and flour-based products.

Despite this potential, critical scientific gaps remain. A comprehensive understanding of interactions between pulse- and microalgae-derived ingredients under different processing conditions is essential for developing next-generation flour-based foods. Studies investigating the combined use of microalgae and pulse-based composite flours are still scarce, particularly in bakery and flour-based systems. Future research should focus on elucidating protein–protein and protein–starch interactions, the effects of processing on technofunctional properties, and the bioaccessibility of nutrients and bioactive compounds in these complex food matrices. In addition, sensory optimization strategies, including approaches to mitigate undesirable flavors while preserving nutritional quality, remain underexplored and represent a major challenge for consumer acceptance and commercial scalability [90,95]. Addressing these knowledge gaps through multidisciplinary research will support the rational design of nutritionally balanced, technologically functional, and sensorially acceptable composite flours, especially with economically feasible use of seasonings as a masking off-flavor strategy, ultimately contributing to more sustainable and resilient plant-based food systems.

This review is driven by the need to consolidate current knowledge and address the challenges involved in developing multi-component plant-based systems. By highlighting current trends and key scientific gaps, this review supports the design of nutritionally

balanced, technologically viable, and sustainable food products, contributing to innovation in plant-based food systems and the bioeconomy.

Author Contributions: A.B.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing—original draft, and Writing—review and editing. E.L.: Data curation, Formal analysis, Investigation, Methodology, Writing—original draft, and Writing—review and editing. M.B.: Data curation, Formal analysis, Investigation, Methodology, Writing—original draft, and Writing—review and editing. G.V.G.: Data curation, Formal analysis, Investigation, Methodology, Writing—original draft, and Writing—review and editing. and A.R.C.B.: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Brazilian Foundations CAPES (Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) process number 001, FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) process number 2023/00857-0, and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) grant number 405238/2025-8, and ARC Braga (PQ 305518/2024-0) was a recipient of a research productivity fellowship from CNPq.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data that underpin this review were obtained from public databases and are available in the references cited in the article.

Conflicts of Interest: Author Gabrielle Victoria Gautério was employed by the company Bean Possible Ingredientes e Soluções Tecnológicas LTDA. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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