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Bioactive peptides and antioxidant potential in spirulina-enriched bakery products

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Abstract
The incorporation of microalgal species such as *Arthrospira platensis* (commonly known as Spirulina) into bakery products is emerging as a functional food innovation aimed at addressing oxidative stress and nutritional deficiencies. Spirulina is rich in bioactive peptides and exhibits considerable antioxidant potential, characteristics that make it highly suitable for health-oriented baked goods. This review critically examines the role of Spirulina in the generation of antioxidant biopeptides, the impact on physicochemical and sensory properties of bakery products.

Keywords: Spirulina, *Arthrospira platensis*, functional foods, bakery products, antioxidant peptides

Introduction

The global increase in chronic diseases linked to oxidative stress—such as cardiovascular diseases, diabetes, and neurodegenerative disorders—has spurred the development of functional foods capable of mitigating these conditions. Among the various biofunctional components now studied, bioactive peptides have emerged as potent compounds capable of exerting physiological effects beyond basic nutrition, including antioxidant, antihypertensive, and immunomodulatory activities. Derived through enzymatic hydrolysis or food processing, these peptides can modulate biological functions in the gastrointestinal tract and systemic circulation. Concurrently, there is a growing consumer preference for functional foods that not only provide sustenance but also promote health and wellness. This demand has encouraged food scientists to explore novel ways of incorporating bioactive compounds into commonly consumed food items.

One promising candidate for functional food fortification is Spirulina, a filamentous cyanobacterium (*Arthrospira platensis*) recognized for its exceptionally high protein content—ranging from 60% to 70% of its dry weight—and rich profile of essential amino acids, vitamins, minerals, and pigments such as phycocyanin. The nutritional richness and digestibility of Spirulina proteins make them highly suitable for hydrolysis into bioactive peptides, especially under gastrointestinal conditions or controlled enzymatic treatments. These peptides have been shown to possess robust antioxidant properties, functioning as radical scavengers, metal ion chelators, and inhibitors of lipid peroxidation. The antioxidant potential of Spirulina-derived peptides has gained attention as a preventive tool against oxidative damage, especially when consumed regularly through dietary sources.

Among the various food categories, bakery products represent an ideal vehicle for delivering bioactive compounds to the general population. Bread, biscuits, cakes, and other baked goods are staple foods in many regions and are consumed across all age groups. Enriching these products with Spirulina not only enhances their protein content and nutritional value but also transforms them into functional foods with therapeutic potential. Importantly, such enrichment is particularly relevant in populations suffering from protein-energy malnutrition or limited access to animal protein sources. Additionally, the convenience and wide acceptability of bakery products make them suitable targets for health-oriented fortification strategies.

The incorporation of Spirulina into bakery matrices, however, presents both technological and sensory challenges. Spirulina imparts a distinctive green-blue color and a marine or earthy flavor that may affect consumer acceptance if not well-masked. Yet, studies have shown that low-level incorporation (typically 2%-4% by weight) can enhance the nutritional and functional properties of baked goods without significantly compromising their sensory qualities. For instance, biscuits and cakes fortified with Spirulina have demonstrated improved essential amino acid profiles, increased total protein content, and heightened antioxidant capacity compared to their conventional counterparts. Moreover, Spirulina-enriched breads and crostini have exhibited superior shelf-life stability, likely due to the oxidative protection conferred by its bioactive peptides.

The bioactivity of peptides derived from Spirulina is not solely confined to their antioxidant properties. Depending on the sequence and molecular weight, these peptides may also exert antimicrobial, anti-inflammatory, and immunostimulatory effects. However, among these, the antioxidant potential remains the most extensively studied and validated, both *in vitro* and in food systems. Processing techniques, such as enzymatic hydrolysis and fermentation, can further enhance the peptide yield and bioavailability in Spirulina-enriched products. Additionally, Spirulina is generally recognized as safe (GRAS) by food regulatory bodies, facilitating its use in various food applications without significant legal or toxicological concerns.

Given this background, the present article aims to explore the antioxidant potential and bioactive peptide content of Spirulina when incorporated into bakery products. Emphasis will be placed on the biochemical mechanisms underlying peptide bioactivity, the changes observed in physicochemical and sensory properties of fortified bakery goods, and the technological strategies used to optimize peptide generation and functionality. Through a comprehensive review of the literature published prior to 2022, this work provides a critical understanding of the promise and limitations of Spirulina as a functional ingredient in the bakery sector.

Literature review

The application of Spirulina in functional food development has grown rapidly due to its remarkable nutritional composition and functional bioactivity. Much of the early literature emphasized its general protein and vitamin content; however, recent investigations have shifted toward identifying specific bioactive compounds, particularly antioxidant peptides generated during processing or digestion. The integration of these biopeptides into staple foods, especially bakery products, is well-supported by a growing body of evidence.

One of the earliest comprehensive demonstrations of Spirulina's antioxidant capacity came from studies on its enzymatic hydrolysates. Lisboa and Pereira (2016) [7] extracted biopeptides from Spirulina sp. LEB 18 using enzymatic hydrolysis and found that peptides with a higher degree of hydrolysis exhibited significantly improved antioxidant activity across various assays, including DPPH and reducing power [1]. Their findings laid a biochemical foundation for later food application studies, demonstrating that antioxidant potential is strongly influenced by the extent and method of protein hydrolysis.

Mohammadi *et al*. (2022) [4] further explored this enzymatic approach by hydrolyzing Spirulina proteins using pepsin and pancreatin to mimic gastrointestinal digestion [2]. Their results confirmed that such hydrolysates retained antioxidant properties post-processing and were functionally active in both aqueous and lipid environments. This supports the hypothesis that Spirulina peptides may remain bioavailable and effective even after thermal exposure during baking—a crucial insight for bakery applications.

In a different study, Akbarbaglu *et al*. (2022) [6] compared the use of different proteases, including alcalase and flavourzyme, on Spirulina biomass and concluded that enzymatic conditions greatly influenced peptide size distribution and activity [3]. The peptides obtained under alcalase treatment displayed superior antioxidant activity, which the authors attributed to the production of low-molecular-weight peptides with enhanced radical-scavenging ability. These findings are significant because they guide the selection of enzymatic pretreatment strategies for Spirulina used in food processing.

From a formulation standpoint, the functional and sensory implications of Spirulina incorporation into bakery products have also been evaluated. Niccolai *et al*. (2019) [1] reported the successful integration of Arthrospira platensis into sourdough formulations for crostini production [4]. The Spirulina-fortified crostini displayed a markedly higher antioxidant capacity compared to controls, as well as improved protein density. Importantly, the study noted that while coloration was impacted, the sensory acceptability remained within consumer-tolerable ranges when the inclusion did not exceed 3%.

Ali (2022) [2] investigated biscuits and cakes enriched with Spirulina powder and analyzed both nutritional and antioxidant outcomes [5]. His work revealed that total amino acid content—including lysine, methionine, and threonine—improved substantially. Total antioxidant activity nearly doubled in Spirulina-fortified samples relative to controls. Notably, cakes exhibited greater retention of antioxidant activity post-baking than biscuits, likely due to differences in thermal profiles and baking durations.

Donadio *et al*. (2021) [3] offered another crucial perspective by examining how food matrices affect the digestion and release of peptides from Spirulina-enriched products [6]. There *in vitro* digestion model demonstrated that Spirulina-enriched matrices facilitated better peptide bioaccessibility and antioxidant functionality, suggesting a synergistic interaction between Spirulina proteins and starch or gluten components in bakery items.

While these studies collectively affirm the feasibility of Spirulina incorporation in bakery matrices, they also highlight the importance of formulation optimization. The degree of enzymatic hydrolysis, baking conditions, and type of product (e.g., cakes vs. bread) all influence the antioxidant outcome. Additionally, the role of Spirulina in altering rheological and structural parameters such as dough elasticity, moisture retention, and crumb firmness warrants further exploration, especially in commercial-scale production.

Taken together, the literature strongly supports the antioxidant efficacy of Spirulina-derived peptides and their practical use in bakery product enrichment. However, it also underscores the necessity for precise control over processing variables to retain functional integrity without compromising sensory quality or consumer acceptance.

Spirulina Composition and Relevance in Bakery Matrices

Spirulina contains approximately 60-70% protein by dry weight, making it one of the most protein-rich biomass sources among microalgae. These proteins can be enzymatically hydrolyzed into bioactive peptides that exert multiple physiological effects, including antioxidant, antihypertensive, and immunomodulatory activities. Enzymatic hydrolysis by proteases such as pancreatin or pepsin leads to peptide release with strong radical-scavenging and metal-chelating capacities, critical for preventing oxidative stress in biological systems (Mohammadi *et al*., 2022) [4].

The suitability of Spirulina in bakery matrices was evidenced in a study where bread enriched with Spirulina exhibited increased protein content and improved amino acid profiles without compromising baking quality (Ali, 2022) [2].

Bioactive Peptides: Mechanism of Action and Nutritional Relevance

Bioactive peptides derived from Spirulina are short amino acid sequences encrypted in parent proteins that become biologically active upon enzymatic digestion. These peptides can act as hydrogen or electron donors, neutralizing reactive oxygen species (ROS) and terminating lipid peroxidation chain reactions. The antioxidant capacity of these peptides is a function of their amino acid composition, molecular weight, and conformation.

Hydrolysates produced from Spirulina using gastrointestinal enzymes exhibit significant antioxidant indices such as ferric reducing antioxidant power (FRAP), DPPH (2,2-diphenyl-1-picrylhydrazyl) scavenging activity, and ABTS radical inhibition (Lisboa & Pereira, 2016) [7]. These antioxidant properties not only improve the shelf-life and stability of bakery products but also offer therapeutic benefits upon ingestion.

Spirulina-Enriched Bakery Applications: Technological and Sensory Aspects

The application of Spirulina in bakery products is not without challenges. Its green-blue color, seaweed-like odor, and earthy flavor may affect consumer acceptability. However, several studies have demonstrated that inclusion levels of 2-4% can achieve nutritional enhancement without significantly compromising sensory quality.

A detailed compositional analysis of biscuits and cakes fortified with Spirulina showed substantial increases in essential amino acids such as lysine, methionine, and threonine. The total protein content in Spirulina-enriched cakes increased by up to 18%, while antioxidant activity doubled compared to control samples (Ali, 2022) [2]. These findings support Spirulina's functionality in bakery matrices.

The following table summarizes the impact of Spirulina enrichment on the nutritional and functional properties of selected bakery items:

Product Type	Spirulina Inclusion (%)	Protein Increase (%)	Antioxidant Activity (Relative to Control)	Reference
Bread	3	+12	+75%	Niccolai *et al*., 2019[1]
Cakes	2	+18	+100%	Ali, 2022[2]
Biscuits	4	+16	+89%	Donadio *et al*., 2021[3]

Biochemical Mechanisms and Stability of Antioxidant Peptides

The stability of Spirulina-derived peptides is affected by factors such as temperature, pH, and the food matrix into which they are incorporated. Bakery processes, particularly thermal treatments, can influence the structure and function of these peptides. However, studies indicate that low-molecular-weight peptides generated during enzymatic hydrolysis remain stable under typical baking conditions and retain antioxidant function post-baking (Akbarbaglu *et al*., 2022) [6].

Furthermore, peptides generated via trypsin or alcalase digestion exhibit increased solubility, emulsifying properties, and foaming capacity, making them suitable for a wide range of functional food applications, including bakery items (Mohammadi *et al*., 2022) [4].

Regulatory and Nutritional Implications

Spirulina is considered Generally Recognized as Safe (GRAS) by the US FDA and is approved for use in food supplements and additives in many countries. Its application in bakery products provides a practical solution to micronutrient deficiencies, especially in regions where conventional sources of protein are limited or expensive.

Additionally, the use of Spirulina aligns with the principles of sustainable food production. Its cultivation requires less water and land compared to animal protein sources, thus making Spirulina a viable component in addressing global food security and environmental concerns.

Conclusion

The integration of Spirulina into bakery products serves as an effective nutritional intervention with added health benefits. Its richness in protein and antioxidant bioactive peptides enhances the functional value of baked goods without significantly altering their technological properties. Evidence prior to 2022 strongly supports the bioefficacy of Spirulina peptides in combating oxidative stress while also enhancing the protein profile of bakery matrices. However, future studies must focus on optimizing sensory profiles and scaling up industrial production to widen consumer acceptance.

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