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Potential of Fish Protein Hydrolysates as Bioactive Ingredients for Antidiabetic Functional Snacks: A Narrative Review

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ABSTRACT

The rising prevalence of diabetes mellitus highlights the need for food-based strategies that reduce postprandial glycaemic excursions. Snacks are a critical dietary target due to their frequent consumption, yet most commercial options are rich in rapidly digestible carbohydrates. Fish protein hydrolysates (FPHs) offer peptide-mediated bioactivity beyond simple macronutrient substitution, but their application in antidiabetic snack development remains limited. This review evaluates the potential of FPHs as functional ingredients in antidiabetic snack formulations. A narrative synthesis of literature from major scientific databases was performed, focusing on antidiabetic mechanisms of FPH-derived peptides and their incorporation into finished snack products. Evidence suggests that FPHs may support glycaemic regulation through inhibition of α-amylase, α-glucosidase, and DPP-IV, modulation of incretin pathways including GLP-1, and antioxidant activity, mainly demonstrated in in vitro and in vivo models. Product studies indicate that FPH incorporation at optimal levels of approximately 2–15% improves protein density and digestibility in snack matrices such as cookies, biscuits, bars, noodles, and bread. However, sensory acceptance is formulation-dependent, and bitterness or fishy off-flavours may require mitigation strategies such as enzymatic debittering or fermentation. Despite promising functional properties, human evidence confirming glycaemic benefits of FPH-enriched snacks remains limited. Standardized characterization and well-controlled clinical trials using finished products are essential to translate mechanistic potential into validated dietary applications.

Key Messages:

- Fish protein hydrolysates (FPH) offer a viable functional ingredient for snack reformulation by improving protein quality and delivering bioactive peptides with relevance to glycaemic regulation.
- Incorporation of FPH at optimized inclusion levels enhances the nutritional profile and selected technological properties of snack products, supporting their applicability within diabetes-oriented dietary strategies.
- Current evidence underscores the need to better integrate biological efficacy with food application, particularly through standardized evaluation of glycaemic responses in finished FPH-enriched snack products.

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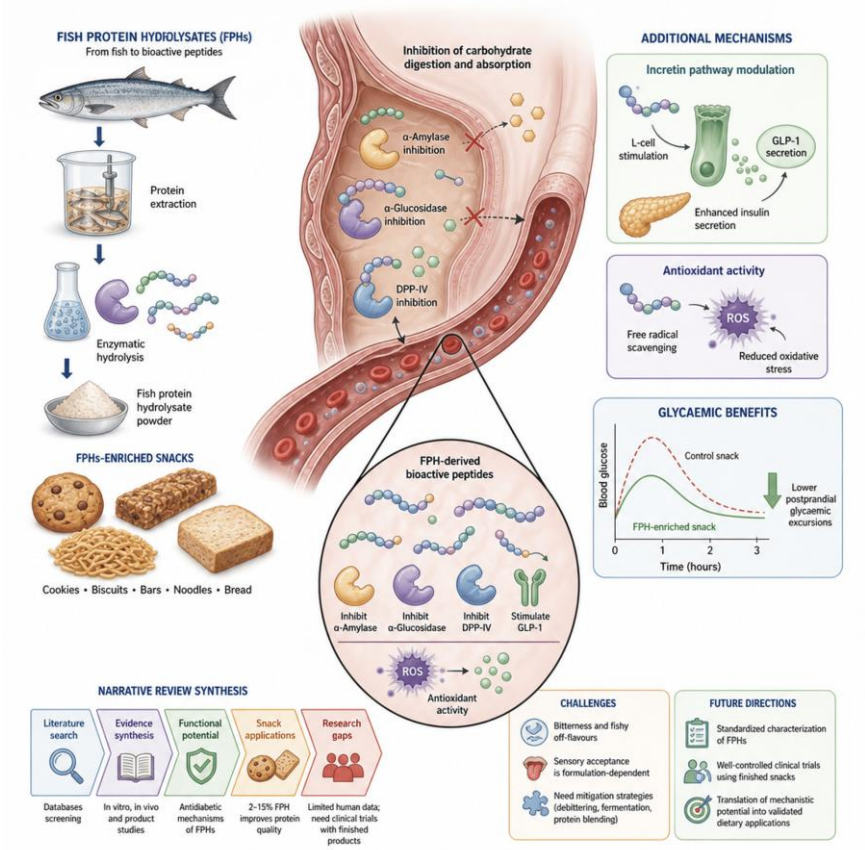
GRAPHICAL ABSTRACT



INTRODUCTION

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycaemia resulting from impaired insulin secretion, impaired insulin action, or a combination of both. Approximately 90% of diabetes cases are classified as type 2 diabetes mellitus, which is primarily driven by insulin resistance and progressive pancreatic beta-cell dysfunction, and is closely associated with lifestyle-related factors, including unhealthy dietary patterns, overweight and obesity, and insufficient physical activity (1). The global burden of diabetes continues to rise substantially, with the number of affected individuals increasing from 460 million in 2019 to 529 million in 2021 and projected to reach 1.31 billion by 2050 (2). Indonesia represents one of the countries with the highest diabetes burden, reporting 19.5 million adult cases in 2021 and a national prevalence of 11.7% according to the 2023 Indonesian Health Survey (3). This escalating prevalence underscores the urgent need for effective, sustainable, and culturally appropriate dietary strategies to support diabetes management. Community-based evidence from Indonesia further highlights modifiable lifestyle and dietary factors as key determinants of type 2 diabetes risk, reinforcing the importance of practical food-based interventions (4).

Dietary modification plays a central role in glycaemic control, complication prevention, and quality-of-life improvement among individuals with diabetes mellitus (5, 6). Nevertheless, a persistent challenge lies in the limited availability of foods that simultaneously meet specific nutritional requirements, provide metabolic benefits, and remain organoleptically acceptable and practical for routine consumption. In modern dietary patterns, snack foods are consumed frequently between main meals and represent a primary driver of postprandial glycaemic excursions, as they are often formulated with high proportions of rapidly digestible carbohydrates, low dietary fibre, and minimal functional protein (7). Because of their high consumption frequency and cumulative metabolic impact, snacks constitute a high-leverage target for nutritional intervention (8). Consequently, the development of functional snack products with reduced glycaemic impact and additional biological activities that support glycaemic

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regulation has gained increasing attention as a complementary nutritional strategy for diabetes management.

Among emerging functional ingredients, fish protein hydrolysates (FPH), produced through enzymatic hydrolysis of fish proteins or fishery by-products, have attracted increasing interest due to their content of low–molecular weight peptides with diverse bioactivities (9-12). While many dietary proteins primarily contribute to metabolic health through macronutrient substitution effects, such as increasing satiety or improving the protein-to-carbohydrate ratio, FPHs offer an additional peptide-mediated biofunctional advantage. The enzymatic hydrolysis process generates short peptides capable of exerting specific biological actions that are not typically accessible in intact protein matrices without controlled hydrolysis, thereby positioning FPH as both a nutritional and biofunctional ingredient (13).

Accumulating evidence indicates that bioactive peptides derived from FPH may exert antidiabetic effects through multiple mechanisms, including inhibition of α-amylase, α-glucosidase, and DPP-IV, enhancement of insulin sensitivity, modulation of incretin hormone secretion, and attenuation of oxidative stress and inflammation involved in diabetes pathophysiology (14-17). In addition to these biological effects, FPH possess favourable amino acid profiles and high bioavailability, supporting their potential applicability within food systems (7). Despite growing evidence on the antidiabetic bioactivity of FPH, existing literature has predominantly focused on mechanistic outcomes derived from in vitro and in vivo models. Comparatively limited attention has been directed toward their translational relevance in food product development, particularly within functional snack formulations for people with diabetes. Importantly, the effectiveness of bioactive compounds in real-world settings is strongly influenced by food matrix interactions, processing conditions, and sensory attributes, which collectively determine consumer acceptance and practical applicability (18).

Based on this gap, this narrative review aims to synthesize and critically interpret current literature on the potential of fish protein hydrolysates as functional ingredients for antidiabetic snack development. The review integrates evidence on FPH characteristics, bioactive peptide mechanisms, and reported effects on glycaemic response and product feasibility. By adopting a translational perspective that bridges nutritional biochemistry and food technology, this article seeks to provide a comprehensive conceptual framework to support the development of FPH-based functional snacks as part of diabetes-oriented dietary strategies.

METHODS

Study Design

This study was conducted as a narrative review aimed at synthesizing and interpreting current scientific evidence on the potential of fish protein hydrolysates (FPH) as functional ingredients for the development of antidiabetic snack products. A narrative review approach was selected to enable the integration of evidence derived from heterogeneous study designs, including in vitro, in vivo, and food application studies, while emphasizing the translational relevance of FPH within the context of functional foods and snack formulation.

Literature Search Strategy

A comprehensive literature search was performed in PubMed, Scopus, ScienceDirect, and Google Scholar. The search covered publications from January 2018 to December 2025, and searches were updated in December 2025 prior to manuscript finalization. Keyword combinations were constructed using Boolean operators and included terms such as “fish protein hydrolysates”, “bioactive peptides”, “antidiabetic”, “glycaemic response”, “functional foods”, and “snack”. The search was limited to peer-reviewed articles published in English. Grey literature, conference proceedings, editorials, and non–peer-reviewed sources were excluded to ensure scientific rigor and data reliability. Duplicate records were removed prior to screening. Titles and abstracts were initially screened for relevance, followed by full-text evaluation of potentially eligible studies.

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Inclusion and Exclusion Criteria

Studies were included if they investigated fish protein hydrolysates or fish-derived bioactive peptides and reported outcomes related to glycaemic regulation, including antihyperglycaemic effects, inhibition of carbohydrate-digesting enzymes, improvement of insulin sensitivity, modulation of incretin hormones, or attenuation of oxidative stress. Studies examining the incorporation of FPH into food products, particularly snack formulations or comparable food systems, were also considered. Studies were excluded if they did not specifically address fish protein hydrolysates, focused solely on non-hydrolysed fish proteins, or lacked relevance to diabetes mellitus or functional food development, or provided insufficient methodological detail to support interpretation of outcomes.

Quality Assessment

Although this review adopted a narrative synthesis approach, the methodological quality of included studies was evaluated using **structured qualitative criteria** adapted to the study design. For mechanistic in vitro and in vivo studies, assessment focused on clarity of FPH preparation methods (e.g., enzyme type, degree of hydrolysis, peptide characterization), appropriateness of experimental controls, and reproducibility of reported outcomes. Particular attention was given to the reporting of hydrolysis parameters and peptide characterization, as variability in these factors may influence biological activity and comparability across studies.

For food application studies, additional criteria included adequacy of formulation description, processing conditions, sensory evaluation design (including panel training and sample size), and transparency of statistical analysis. Studies with incomplete reporting of FPH characterization or methodological procedures were interpreted with caution during synthesis. This structured appraisal informed the critical discussion regarding heterogeneity of FPH preparation methods and variability in sensory evaluation practices.

Study Selection and Data Synthesis

Retrieved articles were initially screened based on titles and abstracts, followed by full-text evaluation to assess their relevance to the objectives of this review. Selected studies were then thematically organized into three main domains: (1) characteristics and functional properties of FPH relevant to food applications; (2) antidiabetic mechanisms of FPH-derived bioactive peptides; and (3) application of FPH in functional snack development, including reported effects on glycaemic response and sensory attributes. Data were synthesized narratively, with emphasis on conceptual linkages among findings and their implications for antidiabetic snack formulation.

Data Presentation

The findings of this review are presented through critical narrative discussion supported by summary tables that highlight antidiabetic mechanisms of FPH, applications in snack products, and their implications for glycaemic response and product acceptability. This approach was adopted to facilitate interpretation of the evidence and to clarify the potential role of FPH as a functional ingredient in antidiabetic snack development.

RESULTS

Antidiabetic Mechanisms of Fish Protein Hydrolysates

The synthesized evidence from the reviewed literature demonstrates that fish protein hydrolysates (FPHs) exhibit antidiabetic activity through multiple complementary mechanisms. As summarized in Table 1, studies employing in vitro assays, in vivo animal models, and limited human interventions consistently reported modulation of key pathways involved in glycaemic regulation. The most frequently reported mechanism was the inhibition of carbohydrate-digesting enzymes, particularly α-amylase and α-glucosidase, which was observed across several FPH sources and peptide fractions (15, 19). In vivo studies further reported improvements in insulin sensitivity, often associated with activation of AMPK and PI3K/Akt pathways and enhanced GLUT4 translocation in peripheral tissues (16, 20).

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Additional findings included dipeptidyl peptidase-IV (DPP-IV) inhibition, increased glucagon-like peptide-1 (GLP-1) activity, and antioxidant-mediated protection of pancreatic β-cells, highlighting the multifunctional metabolic actions of FPH-derived peptides (17, 21, 22). Overall, the findings summarized in Table 1 indicate that FPH-derived bioactive peptides target both digestive and metabolic pathways relevant to postprandial glycaemic regulation.

Across the reviewed studies, enhanced antidiabetic activity was frequently associated with low–molecular weight peptide fractions, particularly those below 3 kDa, which were more consistently linked to enzyme inhibitory activity and incretin modulation (10, 15, 19, 21). However, molecular weight distribution was not uniformly reported across all studies, and several investigations evaluated crude hydrolysates without explicit fractionation. This variability limits direct comparison of bioactive potency among different FPH sources and highlights the importance of standardized peptide characterization in future research.

Table 1. Antidiabetic Mechanisms of Fish Protein Hydrolysates Relevant to Functional Snack Development

FPH Source	Molecular Weight (MW)	Study Model	Dominant Antidiabetic Mechanism	Relevance to Antidiabetic Snack Development	Ref
Mesopelagic fish hydrolysates	Not reported	In vitro (enzyme inhibition assays)	Strong DPP-IV inhibitory activity	Suitable for low-glycaemic, high-protein snack formulations	(23)
Milkfish frame FPH	<1 kDa (most active DPP-IV inhibitory fraction)	In vitro (enzyme assays); in silico	DPP-IV inhibition and cytoprotective effects	Stable peptide source for protein-enriched functional snacks	(10)
Blue whiting FPH (DPP-IV/insulin study)	Whole hydrolysate; predominantly <1 kDa peptides	In vitro (enzyme assays) + simulated gastrointestinal digestion	DPP-IV inhibition and insulinotropic activity	Supports postprandial glucose control in peptide-enriched functional snacks	(21)
Blue whiting FPH (satiety/GLP-1 study)	Whole hydrolysate; >1 kDa peptides implicated in GLP-1 activity	In vitro (enteroendocrine cell models)	Stimulation of GLP-1 secretion	Highlights formulation and processing challenges in snack development	(17)
Blue whiting protein hydrolysates (BW-SPH-A–F)	Whole hydrolysate; MW distribution not reported	In vivo (acute and chronic metabolic models)	Insulinotropic and appetite-modulating effects	Suitable for high-protein snacks targeting type 2 diabetes management	(22)
Trachinotus ovatus FPH	≤3 kDa (TOH-2 most active fraction)	In vitro (enzyme assays); in vivo (diabetic mice); in silico	α-Amylase and DPP-IV inhibition with enhanced insulin secretion	Suitable for glycaemia-oriented snack formulations	(15)
Herring milt FPH	Whole hydrolysate; MW distribution not reported	In vivo (diet-induced obese mice)	Improved insulin sensitivity and preservation of pancreatic β-cell function	Cost-effective marine protein source for antidiabetic snacks	(20)
Skipjack tuna by-products	Whole hydrolysate; MW distribution not reported	In vivo (STZ-induced diabetic rats)	Improved insulin sensitivity and pancreatic β-cell protection via antioxidant and anti-inflammatory pathways	Supports incorporation of FPH into high-protein snacks targeting glycaemic control	(9)
Skipjack tuna by-products	Whole hydrolysate; MW	In vivo (STZ-induced diabetic rats)	Reduced fasting glucose via suppression of inflammatory	Supports development of high-protein, low-	(16)

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FPH Source	Molecular Weight (MW)	Study Model	Dominant Antidiabetic Mechanism	Relevance to Antidiabetic Snack Development	Ref
	distribution not reported		markers and oxidative stress	glycaemic-index snacks	
Yellowfin tuna FPH	Fractionated (Sephadex G-15); active low-MW fractions (<1 kDa range)	In vitro; in vivo (diabetic models); in silico	Multitarget enzyme inhibition combined with antioxidant protection	Strong multifunctional candidate for antidiabetic snack applications	(19)
Salmon & mackerel by-products	Whole hydrolysate; MW distribution not reported	In vivo (diet-induced insulin-resistant mice)	Modulation of insulin sensitivity and gut microbiota composition	Potential functional snack ingredient for addressing insulin resistance	(14)
Boarfish & salmon skin hydrolysates	Whole hydrolysate; predominantly <1 kDa peptides (67–74%)	In vivo (ob/ob mice)	Insulinotropic effects via incretin modulation and appetite regulation	Supports satiety- and glycaemia-modulating snack formulations	(24)
Atlantic cod muscle protein hydrolysate (MPH)	Whole hydrolysate; predominantly ≤2 kDa peptides	Human acute postprandial study	Reduced postprandial insulin demand without hypoglycaemia	Supports development of peptide-enriched snack formulations	(25)
Cod protein hydrolysate	Whole hydrolysate; MW distribution not reported	Human randomized controlled trial (RCT)	No significant glycaemic improvement at low supplementation dose	Indicates need for optimized dosage and food-matrix incorporation	(26)
Baltic herring FPH	Whole hydrolysate; MW distribution not reported	In vitro; in vivo; in silico	Incretin preservation and enhancement of insulin sensitivity	Sustainable marine ingredient for antidiabetic snack development	(11)

Application of Fish Protein Hydrolysates in Snack Products

The reviewed product-based studies demonstrated that incorporation of fish protein hydrolysates (FPHs) into snack products consistently altered nutritional composition and selected technological properties. As presented in Table 2, FPH incorporation was most commonly evaluated in cookies, bars, biscuits, noodles, and bread products (7, 27, 28). Across these studies, FPH inclusion generally increased protein content and protein digestibility, while moderate inclusion levels (typically ranging from 2% to 15%) were reported to maintain acceptable sensory quality across different snack matrices (7, 29, 30).

Several formulations also reported reductions in the relative carbohydrate fraction or energy density, particularly in baked products and snack bars, indicating a potential compositional advantage for glycaemic management (31, 32). In contrast, higher inclusion levels were frequently associated with sensory limitations, including bitterness and fishy off-flavours, which were partially mitigated through debittering treatments, fermentation, or controlled processing conditions (28, 33). Collectively, the results summarized in Table 2 indicate that FPH incorporation into snack products is technologically feasible at optimized inclusion levels and consistently improves nutritional attributes relevant to glycaemic management.

It is important to distinguish between direct peptide-mediated bioactive effects and indirect compositional benefits arising from macronutrient modification. While mechanistic studies demonstrate enzyme inhibition and incretin modulation attributable to specific peptide fractions (15, 19, 21), most product-based studies report improvements primarily related to increased protein-to-carbohydrate ratios, enhanced satiety potential, or reduced energy density (7, 28, 30, 32). Direct clinical evidence linking FPH-enriched snack products to measurable postprandial glycaemic reduction in humans remains limited (25, 26).

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Table 2. Application of Fish Protein Hydrolysates in Functional Snack Products

Product Type	FPH Source	Inclusion Level	Processing	Main Findings	Relevance to Antidiabetic Snacks	Ref
Cookies	Piaractus brachypomusmeat protein hydrolysate (RPMPH)	4–12%	Fermentation, baking	Increased protein content and digestibility; reduced lipid oxidation; optimal sensory acceptance at 8%	High protein density and antioxidant activity may support moderated postprandial glycaemic response	(7)
Cookies	Debittered salmon frame protein hydrolysate	2–8%	Enzymatic hydrolysis, Maillard reaction, baking	Increased protein and moisture; reduced carbohydrate fraction; best acceptability at 4%	Potential indirect reduction of glycaemic response through protein enrichment	(29)
Snack bar	Micromesistius poutassouprotein hydrolysate (BWFPH)	Up to 50% (optimal ~17%)	Mixing, molding	Improved protein content and texture; reduced acceptability at excessive inclusion	Optimized FPH levels may enhance satiety and snack quality relevant to glycaemic management	(28)
Snack bar	Debittered tilapia protein hydrolysate	5–15 g/100 g	Enzymatic hydrolysis, debittering	Higher protein content and lower energy density; best sensory quality at 10 g/100 g	Reduced carbohydrate density and improved satiety-related properties	(31)
Snack bar	Blue whiting protein hydrolysate	0–10%	Cold forming	Acceptable sensory quality only at low levels (≤1%) due to fishy flavour	Demonstrates feasibility of low-level FPH incorporation in functional snacks	(33)
Biscuits	Tuna by-product protein hydrolysate	2.5–5%	Enzymatic hydrolysis, baking	Improved sensory quality and oxidative stability compared with fish meal	Indirect glycaemic benefit via improved protein quality and satiety	(27)
Biscuits	Seabass by-product protein hydrolysate	2.5–5%	Enzymatic hydrolysis, baking	Increased protein and PUFA content; reduced carbohydrate proportion	Higher protein-to-carbohydrate ratio may support glycaemic moderation	(32)
Ready-to-eat noodle	Fish protein hydrolysate (unspecified source)	Various ratios (optimal 7:4)	Mixing, drying	High acceptability and shelf stability in optimized formulation	Protein enrichment may delay gastric emptying and support glycaemic control	(34)
Ready-to-eat noodle	Fish protein hydrolysate (unspecified source)	Various ratios (optimal 7:4)	Baking, frying	Increased protein content and digestibility	Improved satiety-related responses relevant to glycaemic regulation	(35)
Bread	Cod by-product protein hydrolysate	1.5–6%	Mixing, fermentation, baking	Acceptable quality at low inclusion (1.5%); flavour impairment at higher levels	Protein enrichment and antioxidant properties may indirectly support glycaemic health	(30)

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DISCUSSION

Integration of Antidiabetic Mechanisms with Functional Snack Applications

The findings synthesized in this review position fish protein hydrolysates (FPHs) as functional ingredients that extend beyond conventional protein fortification by delivering peptide-mediated bioactivity within realistic food matrices. Unlike intact dietary proteins that primarily exert metabolic effects through macronutrient substitution, FPHs contain low–molecular weight peptides capable of directly modulating glycaemic regulation pathways (10, 15, 19, 21). The mechanisms summarized in Table 1—including inhibition of α-amylase, α-glucosidase, and DPP-IV, enhancement of insulin sensitivity, and incretin modulation—represent direct bioactive effects that may operate alongside the indirect compositional benefits observed in protein-enriched snacks, such as reduced relative carbohydrate density and increased satiety (11, 15, 21, 36).

This dual mechanism is particularly relevant for snack products, which are recognized contributors to postprandial glycaemic excursions (8). Product-based studies summarized in Table 2 demonstrate that incorporation of FPHs into cookies, biscuits, bread, and snack bars consistently increases protein density and digestibility, thereby shifting the protein-to-carbohydrate ratio in a direction compatible with glycaemic moderation (7, 27, 29, 30). However, the functional translation of these mechanisms is constrained by a dose–acceptability paradox: inclusion levels potentially required to maximize peptide bioactivity may exceed thresholds of sensory acceptance. Most studies report optimal sensory performance at low to moderate inclusion levels, typically within the 2–15% range, whereas higher dosages frequently induce bitterness and fishy off-flavours that limit consumer acceptability (28, 33). A comparable trend has been observed in fish-flour–fortified cookie formulations, where moderate substitution levels achieved the highest overall sensory acceptance, while higher incorporation levels significantly reduced consumer preference (37, 38).

Food matrix interactions and processing conditions further shape the expression of FPH functionality. Thermal treatments such as baking or frying can influence peptide integrity through denaturation or Maillard reactions. Short-chain peptides—particularly those below 3 kDa—have demonstrated relative resilience to heat processing when incorporated within complex food matrices, although systematic kinetic data on thermal degradation remain limited (18, 39). Protein–carbohydrate interactions during thermal processing may partially protect certain peptide fractions or contribute to the formation of antioxidant compounds; however, excessive heat exposure may attenuate specific enzymatic inhibitory activities. These considerations underscore the importance of optimizing processing parameters to balance peptide stability, bioactivity retention, and product quality.

Collectively, current evidence indicates that FPH incorporation into snack products is technologically feasible and nutritionally advantageous when formulation strategies are tailored to the specific matrix. Although direct human validation of glycaemic outcomes remains scarce, the convergence of peptide-mediated mechanisms and compositional improvements supports the conceptual plausibility of FPH-enriched snacks as components of glycaemia-oriented dietary strategies (32, 34, 35).

Sensory Acceptance and Technological Considerations

Sensory acceptance remains a central determinant of the practical applicability of FPH-enriched snacks. Bitterness and fishy off-flavours are consistently reported challenges and are closely associated with peptide hydrophobicity, molecular weight distribution, and oxidative reactions involving residual lipids (7, 27, 29, 33). The relationship between peptide profile and flavour perception reinforces the need for technological interventions that selectively modify sensory-active fractions while preserving bioactive functionality.

Enzymatic debittering and fermentation represent two principal technological frameworks for addressing these challenges. Enzymatic debittering can hydrolyse hydrophobic peptide sequences responsible for bitterness, thereby reshaping the peptide profile toward smaller or less hydrophobic fractions (40). Fermentation introduces additional proteolytic and metabolic transformations that may generate flavour-active compounds and reduce off-notes. Importantly, these processes do not simply mask undesirable flavours; they alter the structural composition of peptide mixtures, which may influence both

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sensory properties and biological activity. While some evidence suggests that carefully controlled debittering preserves key antidiabetic peptide functions, excessive hydrolysis could reduce the concentration of specific bioactive sequences, highlighting the need for process optimization (29, 31).

Similar sensory limitations have been documented for non-marine protein hydrolysates, including soy and whey, indicating that bitterness is an inherent challenge of peptide-rich ingredients rather than a limitation unique to FPHs (39-41). This broader perspective emphasizes that successful product development requires integrated optimization of peptide profile, formulation strategy, and processing conditions. Approaches such as flavour masking, blending with complementary proteins, or encapsulation technologies may further mitigate sensory constraints while enabling effective delivery of bioactive peptides.

Translational Limitations, Methodological Biases, and Future Perspectives

Despite encouraging mechanistic and product-based findings, significant translational limitations persist. Most evidence supporting the antidiabetic activity of FPHs originates from in vitro systems and animal models, whereas well-controlled human intervention studies remain limited (25, 42). Even existing human trials report modest or variable effects, particularly when FPHs are administered at low doses or outside realistic food matrices. Consequently, the clinical relevance of peptide-mediated mechanisms observed under experimental conditions cannot yet be assumed to translate directly to habitual snack consumption (25, 26, 42).

Methodological heterogeneity further complicates interpretation. Differences in fish species, raw material sources, enzymatic protocols, and degrees of hydrolysis generate substantial variability in peptide composition and bioactivity (11, 21). Inconsistent reporting of molecular weight distribution and peptide characterization limits the ability to establish dose–response relationships or define optimal formulation parameters. From a food science perspective, most product studies focus on compositional and sensory attributes without integrating direct measurements of postprandial glycaemic response (7, 27, 30). Additionally, reliance on untrained sensory panels may introduce subjective bias and reduce generalizability (28, 33).

Future research should adopt integrated translational frameworks that combine standardized FPH production, advanced peptide characterization, and clinically relevant outcome assessment within finished food products. Particular emphasis should be placed on evaluating peptide stability during processing and storage, defining effective yet sensory-acceptable dosage ranges, and conducting human trials that measure glycaemic index, glycaemic load, and insulin dynamics following consumption of FPH-enriched snacks (25, 26, 42). Such approaches are essential for bridging the gap between promising biochemical mechanisms and evidence-based dietary recommendations.

In summary, fish protein hydrolysates represent a promising class of multifunctional ingredients for antidiabetic snack development. However, their successful translation into practical dietary interventions requires coordinated advances in peptide science, food technology, and human clinical validation.

CONCLUSION

Fish protein hydrolysates (FPHs) represent a promising multifunctional ingredient platform for the development of antidiabetic-oriented snack products by integrating macronutrient reformulation with peptide-mediated bioactivity. Across diverse snack matrices—including cookies, biscuits, bars, noodles, and bakery products—FPH incorporation consistently increases protein density and digestibility while partially reducing the relative proportion of rapidly digestible carbohydrates. These compositional modifications may contribute to moderating postprandial glycaemic excursions through improved protein-to-carbohydrate ratios and enhanced satiety effects. Importantly, beyond macronutrient substitution, accumulating evidence indicates that low–molecular weight peptides derived from FPH exert direct biological actions, including inhibition of α-amylase, α-glucosidase, and DPP-IV, alongside modulation of incretin signaling and oxidative stress pathways.

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From a technological perspective, FPHs provide functional attributes relevant to snack formulation, including water-binding capacity, plasticizing effects, and antioxidant properties that may support textural integrity and storage stability. However, translation into commercially viable products is constrained by a dose–acceptability balance, whereby inclusion levels required to maximize bioactivity may negatively affect sensory quality due to bitterness and fish-derived off-flavours. These constraints highlight the necessity for formulation-specific optimization and controlled processing strategies to preserve peptide functionality without compromising consumer acceptance.

Despite promising mechanistic and product-level findings, the antidiabetic efficacy of FPH-enriched snacks remains largely inferential rather than clinically validated. Substantial methodological heterogeneity persists across studies, particularly in the inconsistent reporting of Degree of Hydrolysis (DH), peptide molecular weight distribution, and hydrolysis parameters, which limits cross-study comparability and dose–response interpretation.

Future studies should implement standardized and transparent reporting of Degree of Hydrolysis (DH), peptide molecular weight distribution, and hydrolysis conditions to enhance reproducibility and enable meaningful cross-study comparison. Critically, well-controlled human intervention trials evaluating postprandial glycaemic and insulin responses following consumption of finished FPH-fortified snack products are urgently needed, as current evidence is predominantly derived from in vitro assays, animal models, or isolated peptide systems. Such rigorously designed clinical investigations using realistic food matrices are essential to substantiate metabolic efficacy and support evidence-based dietary recommendations. Addressing these priorities is fundamental to advancing FPH-based functional snacks from promising bioactive concepts to validated dietary strategies for individuals with, or at risk of, type 2 diabetes mellitus.

DECLARATION OF THE USE OF AI

The authors declare that no artificial intelligence (AI), AI-assisted technologies, or large language models (LLMs) were used in the conception of the study, data analysis, or the drafting, writing, and editing of this manuscript. The only exception is the graphical abstract, which was created using the design platform Illustrae (https://illustrae.co/). The authors take full responsibility for the content and accuracy of the graphical abstract and the entire manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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