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Research Article

Salmon Blood-Derived Bioactive Compounds: Emerging Applications in Health Sciences, Functional Nutrition, and Biomedical Research

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Abstract

Objectives: The sustainable utilization of fish processing by-products is increasingly recognized as a strategy to enhance both environmental and public health outcomes. Among these by-products, salmon blood has attracted growing interest due to its rich composition of bioactive proteins and peptides.

Methods: Biochemical composition of salmon blood, with emphasis on components such as hemoglobin, albumin, globulins, and enzymatically derived peptides with the recent advances in extraction and processing technologies provides translational opportunities in health sciences and biomedical innovation.

Results: Salmon blood contains a diverse range of bioactive molecules exhibiting antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory activities. These compounds show promise in functional nutrition, disease prevention, and biomedical applications, including hemoglobin-based oxygen carriers, therapeutic agents, and tissue engineering materials. Furthermore, the valorization of salmon blood aligns with circular bioeconomy models, contributing to sustainable marine resource management.

Conclusion: Salmon blood is a valuable source of bioactive compounds with wide-ranging health applications. However, key challenges—such as allergenicity, regulatory frameworks, and industrial scalability—must be addressed through interdisciplinary research and development.

Keywords: Salmon Blood; Bioactive Peptides; Functional Nutrition; Biomedical Applications; Circular Bioeconomy

Introduction

The rising global emphasis on sustainable development, public health innovation, and circular bioeconomy has intensified the scientific exploration of underutilized biological resources. In particular, marine by-products represent an abundant and largely untapped reservoir of bioactive compounds with significant potential for health-related applications. Among these, salmon (*Salmo salar*) blood has recently emerged as a promising source of functional biomolecules. Traditionally discarded during fish processing, blood fractions are now being re-evaluated for their nutritional, therapeutic, and biomedical value [1-4] (Figure 1).

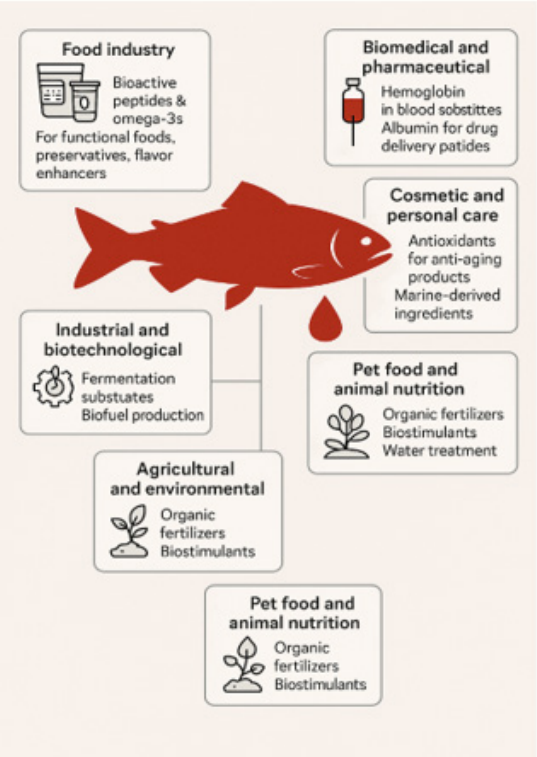

Figure 1: Emerging applications of salmon blood-derived bioactive compounds across sectors.

Salmon blood is rich in high-quality proteins and peptides, including hemoglobin, albumin, globulins, enzymes, and other plasma components. These molecules possess a variety of bioactivities such as antioxidative, antimicrobial, antihypertensive, anti-inflammatory, and immunomodulatory properties [5-8]. Bioactive peptides derived from enzymatic hydrolysis of blood proteins have shown particular promise in modulating oxidative stress and inflammation—two key mechanisms involved in the pathogenesis of chronic diseases. These findings suggest potential applications of salmon blood-derived components in preventive nutrition, functional foods, and therapeutic formulations [9] (Table 1).

Table 1: Key bioactive compounds identified.

Compound Class	Examples	Potential Functions
Hemoglobin-derived peptides	VV-hemorphin-7, LVV-hemorphin-7	Antioxidant, ACE-inhibitory (antihypertensive)
Antimicrobial peptides (AMPs)	Piscidins, Defensins	Broad-spectrum antimicrobial (Gram± bacteria, fungi)
Lipids	EPA/DHA, Phospholipids	Anti-inflammatory, Neuroprotective
Heme Iron	Fe^{2+}/Fe^{3+} complexes	Oxygen transport, Antioxidant
Enzymes	SOD, Catalase	ROS scavenging

In addition to their biological effects, salmon blood proteins have physicochemical properties-such as emulsification, water-binding, and gelling capacity-that are beneficial in food processing and formulation. The dual nutritional and functional roles of these proteins enhance their value in designing novel foods tailored to health-conscious consumers. Furthermore, the biomedical field is increasingly exploring hemoglobin isolated from salmon blood for use in hemoglobin-based oxygen carriers (HBOCs), wound healing formulations, and tissue engineering scaffolds due to its oxygen-carrying capacity and biocompatibility [10].

This emerging focus is also supported by technological advancements. Innovations in protein recovery, including enzymatic hydrolysis, membrane filtration, and chromatographic purification, have enabled the efficient isolation of bioactive components from complex matrices such as blood [11]. These methods allow for scalable, food-grade, and pharmaceutical-grade applications, which is essential for transitioning from research to industry (Table 2).

Table 2: Composition and functional potential of bioactive compounds derived from salmon blood.

Component	Typical Content in Salmon Blood	Potential Use	Citation
Hemoglobin	~100–150 mg/mL	Natural antioxidant, iron supplement	[12,13]
Protein Content	13–20% (wet basis)	Nutraceuticals, pet food, protein hydrolysates	[14-16]
Bioactive Peptides	Variable, depending on hydrolysis process	Antioxidant, antihypertensive, antimicrobial	[8,9]
Iron (heme form)	~0.3–0.5 mg/mL	Iron supplements, food fortification	[17,18]
Fatty Acids	Small amounts, especially EPA/DHA	Functional foods	[19]

Moreover, the valorization of salmon blood contributes meaningfully to global sustainability objectives by reducing food system waste, lowering the environmental footprint of aquaculture, and creating added economic value from previously discarded biomass. This aligns with the principles of the circular bioeconomy, which advocate the full utilization of biological materials across industries to close material loops and reduce dependency on non-renewable resources [12-19]. Despite these promising developments, several challenges must be addressed before salmon blood-based ingredients can be fully integrated into food systems and clinical practice. Key issues include potential allergenicity, variability in composition based on species and processing conditions, limited regulatory guidance, and consumer acceptance. Ethical and safety considerations, especially for biomedical applications, also warrant further investigation [20].

Biochemical Composition of Salmon Blood

Salmon blood is a complex biological fluid rich in various macromolecules, including proteins, lipids, carbohydrates, and nucleic acids. The primary components that have garnered significant interest for their potential health benefits are the proteins and peptides present in the plasma. Blood proteins in salmon primarily include hemoglobin, albumin, globulins, fibrinogen, and a wide variety of enzymes [4]. These proteins exhibit a range of bifunctional properties, making them highly valuable for both nutritional and biomedical applications.

Proteins in Salmon Blood

Over the past two decades, there has been a growing global emphasis on the sustainable utilization of marine-derived food resources, driven by population growth and the increasing demand for high-quality protein sources. Global fish production reached 179 million metric tons (MT) in 2018 and is projected to increase to 194 MT by 2026. More than 70% of captured fish undergo processing operations such as filleting, canning, smoking, salting, and curing, which generate substantial quantities of by-products. These processing by-products—comprising heads, bones, skin, viscera, blood, and other tissues—constitute approximately 30% to 70% of the total fish weight, depending on the species. Furthermore, diverse forms of wastewater are generated during washing, thawing, cooking, and fishmeal production processes, contributing to the environmental burden of fish processing operations [1,5].

The nutritional and functional potential of proteins derived from marine by-products has garnered increasing attention due to their ability to yield bioactive peptides. These peptides, encrypted within native protein structures, are activated through enzymatic hydrolysis, digestion, or microbial fermentation [21]. Once liberated, they may exert a range of bioactivities, including antioxidant, antihypertensive, anti-inflammatory [22], anticancer [10], and antimicrobial effects [23]. Additional health benefits include enhancing muscle regeneration, promoting cellular proliferation [24], improving insulin sensitivity [25], and reducing the risk of cardiovascular disease, metabolic syndrome [26], and type 2 diabetes [27]. The bioactivities of these peptides are influenced by their amino acid sequence, structure, and overall composition [28].

Fish proteins also possess functional properties such as solubility, water-holding capacity (WHC) [11], fat-binding capacity, foaming ability, and emulsification properties [29], making them attractive for use as natural hydrocolloids. The increasing demand across the food, pharmaceutical, nutraceutical, and cosmetic industries for functional and sustainable ingredients underscores the value of fish-derived bioactive peptides. Consequently, the valorization of fish processing by-products into high-value bioactive compounds represents a strategic approach to supporting circular bioeconomy initiatives while improving human health outcomes. Among the various fish by-products, salmon blood is particularly underutilized yet highly promising. Although blood constitutes approximately 2% of the live weight of a fish, its biofunctional potential is often overlooked. In the U.S., the majority of salmon blood is discarded or rendered into fishmeal. However, emerging biotechnology enterprises, are pioneering the medical and diagnostic use of salmon blood proteins, tapping into a global biologicals market estimated at over USD 35 billion [30].

Hemoglobin is the predominant protein in salmon blood and functions as a tetrameric oxygen transporter. Salmon hemoglobin has a molecular weight of approximately 64 kDa and demonstrates excellent solubility and stability under physiological conditions [10]. Structurally and functionally, it is similar to human hemoglobin, which positions it as a promising candidate for use in blood substitutes and oxygen-carrying medical applications [31]. In addition to hemoglobin, salmon plasma contains albumin, which plays a role in maintaining osmotic pressure and transporting fatty acids and hormones [4]. Due to its high biocompatibility and binding versatility, salmon albumin is being explored for applications in drug delivery systems [20,32]. Moreover, salmon blood includes a variety of globulins, such as immunoglobulins, that contribute to

immune responses and present potential for immunotherapeutic applications [6]. Despite limited industrial-scale exploitation of blood-derived bioactive compounds in the U.S., the integration of scientific advancements with sustainability-focused innovation suggests a promising future for the recovery and application of salmon blood proteins in biomedicine and functional foods.

Bioactive Peptides in Salmon Blood

Proteins perform a wide range of biological functions, providing both structural and physiological support essential to health and physical performance [33]. In addition to their nutritional value, proteins are increasingly recognized as important sources of bioactive peptides-short amino acid sequences, typically between 2 and 20 residues, that exert positive effects on biological functions and overall health [21]. These peptides remain inactive within the parent protein structure until released through processes such as enzymatic hydrolysis, fermentation, or gastrointestinal digestion, which unlock their bioactivity [10]. The specific function of a bioactive peptide is influenced by several factors, including the origin of the protein, the molecular weight of the resulting peptide, and especially the amino acid sequence. The composition and order of amino acids dictate the physicochemical properties and biological efficacy of the peptides [34]. For example, hydrophobic amino acids such as leucine, isoleucine, and valine have been shown to enhance peptide interaction with cell membranes, increasing their absorption and bioavailability [24].

In recent years, the growing volume of by-products generated by fish processing industries has raised concerns regarding environmental sustainability. These by-products-comprising heads, bones, skin, viscera, and blood-represent approximately 45% of the total biomass of processed fish and are often discarded without adequate treatment, resulting in economic losses and environmental challenges [4,35]. Fish processing effluents are known to contain significant quantities of biodegradable organic matter, including proteins and lipids, and exhibit high chemical oxygen demand (COD), contributing to water pollution if not properly managed [36]. However, these by-products are now being increasingly explored as a potential source of valuable bioactive proteins and peptides. The recovery of such compounds not only adds economic value but also aligns with sustainable waste management practices. Advances in separation and purification technologies are enabling the extraction of high-value peptides that can be utilized in the development of functional foods, pharmaceuticals, cosmetics, and nutraceuticals [37].

Among the various underutilized resources, blood-derived proteins from fish such as salmon are of particular interest. The principal protein found in salmon blood is hemoglobin, a tetrameric molecule responsible for oxygen transport. Salmon hemoglobin exhibits similar structural and functional features to human hemoglobin and has potential applications as a substitute oxygen carrier in biomedical contexts [38]. Its molecular weight (~64 kDa) is slightly less than that of human hemoglobin, and it demonstrates favorable solubility and stability under physiological conditions [10]. Another major protein in salmon blood is albumin, which plays a key role in maintaining osmotic pressure and transporting molecules such as fatty acids and hormones [4]. Due to its high biocompatibility, salmon albumin is being considered for drug delivery applications, particularly in binding and transporting pharmacologically active compounds [39,40]. Additionally, salmon blood contains globulins, including immunoglobulins, which contribute to immune defense and have potential therapeutic applications in immunotherapy [6]. The increasing interest in valorizing these by-products underscores a broader shift toward circular bioeconomy strategies in the marine sector. Fish-derived bioactive peptides, particularly those from blood, present a sustainable and innovative avenue for the development of health-promoting, high-value products across multiple industries.

Lipid and Carbohydrate Content

Salmon blood also contains significant amounts of lipids, particularly phospholipids, which are crucial for maintaining cell membrane structure and function [4]. The lipid fraction is predominantly composed of omega-3 polyunsaturated fatty acids (PUFAs), such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which have well-established cardiovascular and anti-inflammatory health benefits [10]. These lipids may also play a role in the formation of bioactive peptides, as some studies suggest that lipids can enhance the release of protein fragments during enzymatic hydrolysis [39]. Carbohydrates, particularly glycoproteins and glycolipids, are also present in salmon blood, contributing to the structural integrity and stability of the blood cells [31]. These macromolecules have been implicated in immune modulation and cell signaling, further supporting the potential biomedical applications of salmon blood.

Nucleic acids and Other Biomolecules

In addition to proteins, lipids, and carbohydrates, salmon blood contains nucleic acids such as RNA and DNA, though in much smaller quantities. These molecules can provide valuable information for genetic studies and have potential applications in molecular biology [4]. The overall nutrient composition of salmon blood makes it a promising candidate for inclusion in functional foods and nutraceuticals designed to improve overall health.

Applications of Salmon Blood Products

Salmon blood, often regarded as a by-product of the seafood processing industry, holds tremendous potential for diverse applications across sectors including food, healthcare, biotechnology, agriculture, pharmaceuticals, and cosmetics. Its unique biochemical profile-rich in proteins such as hemoglobin, albumin, and globulins, as well as bioactive peptides-offers multifunctional benefits including antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory properties. These features make salmon blood products increasingly attractive for use in value-added products that support human and animal health, environmental sustainability, and industrial innovation (Table 2).

Food Industry Applications

One of the most established areas for the application of salmon blood products is the food industry. Bioactive peptides derived from enzymatically hydrolyzed salmon blood proteins have

demonstrated antioxidant, antimicrobial, and anti-inflammatory effects, making them ideal candidates for functional foods and dietary supplements. These peptides can help improve immune function, reduce oxidative stress, and support cardiovascular health when incorporated into products such as fortified beverages, dairy items, protein bars, or nutritional supplements [6,41]. Salmon blood is also a rich source of omega-3 polyunsaturated fatty acids (PUFAs), which are well-known for their cardioprotective and anti-inflammatory properties. Fortifying foods with salmon-derived PUFAs and peptides may improve the overall nutritional profile while addressing consumer demand for natural and health-promoting ingredients. Additionally, fish protein hydrolysates (FPHs) produced from blood can enhance the flavor and texture of processed seafood products [11], while blood-derived peptides serve as natural preservatives that inhibit spoilage microorganisms and extend product shelf-life.

Biomedical and Pharmaceutical Applications

The biomedical potential of salmon blood is also gaining considerable attention. Salmon blood proteins are also being explored for their biomedical and pharmaceutical relevance. Hemoglobin, one of the most abundant proteins in salmon blood, has been investigated for its potential use in blood substitutes [41]. Due to its oxygen-carrying capacity and similarity to human hemoglobin, salmon hemoglobin can be developed as a safer and more abundant alternative to human or bovine-derived blood substitutes. These substitutes may be useful in treating patients suffering from severe blood loss, especially in regions with limited access to human blood donations. Moreover, salmon albumin is being explored for use in drug delivery systems due to its high binding capacity for various bioactive molecules [39]. The biocompatibility and versatility of salmon albumin make it an ideal candidate for the controlled release of therapeutic agents, such as anticancer drugs or anti-inflammatory compounds. Additionally, bioactive peptides from salmon blood are being studied for their role in promoting wound healing, enhancing immune function, and combating oxidative stress, which could lead to the development of novel therapeutic products [6,42].

Cosmetic and Personal Care Applications

Recent advances in marine biotechnology have extended the application of salmon blood derivatives to the cosmetics and personal care industries. Bioactive peptides and proteins isolated from salmon blood exhibit antioxidant and anti-aging properties that can benefit skin care formulations. For example, peptides with reactive oxygen species (ROS) scavenging abilities may be incorporated into anti-wrinkle creams or serums aimed at reducing oxidative skin damage. The growing demand for natural, sustainable, and marine-derived cosmetic ingredients supports further exploration of salmon blood components in moisturizers, sunscreens, and hair care products [43-45].

Pet Food and Animal Nutrition

Another promising domain for salmon blood valorization is pet food and animal feed production. The high protein content and favorable amino acid profile of salmon blood make it an excellent ingredient for formulating nutrient-rich pet foods. In particular, enzymatically hydrolyzed blood proteins are more digestible and palatable for pets, contributing to better growth performance and immune health. Additionally, the presence of bioactive compounds can enhance gut health and reduce inflammatory responses in animals. Using such by-products also aligns with sustainable animal nutrition practices by reducing waste and reliance on land-based protein sources [46].

Agricultural and Environmental Applications

The agricultural sector offers additional opportunities for utilizing salmon blood products. Dried or hydrolyzed blood meal has long been used as an organic fertilizer due to its high nitrogen content. Salmon blood-derived fertilizers can support plant growth while enhancing soil microbial activity, contributing to sustainable agricultural systems. Moreover, salmon blood proteins may serve as bio-stimulants to improve plant resistance to environmental stressors [47]. In environmental biotechnology, the antimicrobial properties of peptides derived from salmon blood are being explored for bioremediation applications. These bioactive molecules can be utilized to inhibit the growth of harmful bacteria in contaminated water sources or aquaculture systems. Their inclusion in filtration media or biocoatings for aquaculture tanks may improve water quality and reduce the risk of disease outbreaks in farmed fish populations [39].

Beyond the food and healthcare sectors, salmon blood products have potential uses in environmental management and biotechnology. The high nutrient content in salmon blood, including proteins, lipids, and carbohydrates, can be harnessed in biofuel production. Recent research has explored the use of fish-derived proteins and lipids as feedstocks for the production of biofuels, reducing the reliance on traditional agricultural crops and providing a sustainable alternative [4]. Furthermore, salmon blood proteins have been investigated for their potential role in bioremediation efforts. The antimicrobial properties of blood-derived peptides may be utilized in environmental cleanup, particularly in addressing contamination from harmful bacteria or pathogens in water sources. These natural antimicrobial agents could be employed to treat contaminated water in aquaculture or other industrial processes, offering an eco-friendly solution for managing pollution [39].

Industrial and Biotechnological Applications

Beyond the above sectors, salmon blood has the potential to serve as a substrate for fermentation and biotechnological production systems. For instance, microbial fermentation of salmon blood hydrolysates can yield valuable metabolites such as enzymes, organic acids, or biofuels. This not only supports circular bioeconomy principles but also reduces the environmental burden associated with fish processing waste [4] (Table 3).

Table 3: Industrial applications of salmon blood-derived bioactive compounds across different sectors.

Sector	Application	Product Examples	Citation
Nutraceuticals	Protein hydrolysates, bioactive peptides	Capsules, powders for heart health or immunity	[48,49]
Cosmetics	Antioxidant-rich peptides and proteins	Anti-aging creams, wound-healing gels	[50]
Animal Feed	Protein and iron-rich feed supplements	Aquafeeds, pet food enrichment	[4,15]
Food Industry	Natural food colorants and antioxidants (from hemoglobin)	Natural additives, emulsifiers	[13,51]
Agriculture	Biostimulants or soil amendments	Blood meal-type fertilizers	[52]
Biomedical	Hemoglobin-based oxygen carriers (HBOCs), wound dressings	Experimental drug delivery and medical products	[53,54]

Challenges and Future Directions

While the applications of salmon blood products are diverse and promising, several challenges remain to be addressed before their widespread adoption. One major hurdle is the economic viability of extracting, processing, and refining blood components at a commercial scale. Currently, most salmon blood byproducts are underutilized or discarded as waste during fish processing. Establishing infrastructure and logistics for the consistent collection and processing of blood at high volumes will require significant investment. Moreover, low current market demand means there is limited financial incentive for companies to explore this potential, making it difficult to justify large-scale operations without reliable end-use applications [48-52].

In addition to economic concerns, the regulatory landscape governing the use of fish-derived blood products-particularly in food, nutraceutical, and pharmaceutical sectors-is still evolving. There are strict guidelines concerning the safety, traceability, allergenicity, and labeling of animal-derived ingredients. Regulatory clarity is essential, especially in regions such as the United States, European Union, and Asia-Pacific, where food and drug authorities maintain rigorous standards for novel ingredients. There is also a need for risk assessment protocols and toxicological studies to ensure consumer safety, especially when bioactive compounds from blood are intended for human consumption or therapeutic use. From a technical standpoint, further research is needed to optimize extraction and stabilization methods to preserve the bioactivity of sensitive components such as hemoglobin, peptides, and enzymes. The development of green and scalable processing technologies-such as membrane filtration, enzymatic hydrolysis, and cold-chain preservation-is critical to minimizing degradation and maintaining product integrity. Additionally, improving product purity and consistency will be vital for integration into high-value markets such as functional foods, clinical formulations, and biomedical applications [53,54].

Despite these challenges, the future outlook for salmon blood products remains highly encouraging. As consumer interest in sustainable, natural, and functional ingredients continues to grow, the valorization of fish processing byproducts aligns well with global trends in circular economy and zero-waste initiatives. Salmon blood is rich in proteins, bioactive peptides, heme iron, and omega-3-bound hemoglobin complexes-all of which hold promising health and nutritional benefits, including antioxidant, antimicrobial, antihypertensive, and immune-boosting properties.

To unlock the full potential of these bioresources, interdisciplinary collaboration between seafood processing industries, academic researchers, biotechnologists, and regulatory agencies will be essential. Future directions should include:

a. Pilot-scale demonstrations to evaluate technical feasibility and economic return;

b. Clinical and preclinical studies to substantiate health claims;

c. Consumer acceptance research to assess attitudes toward blood-derived products;

d. Exploration of novel applications in wound healing, drug delivery, and tissue engineering.

Conclusion

In conclusion, the valorization of salmon blood products presents a unique opportunity to enhance sustainability and profitability in the seafood sector while addressing consumer demand for health-promoting ingredients. With targeted investment and coordinated research efforts, these byproducts can transition from waste streams into valuable bioingredients across food, pharmaceutical, and biotechnological industries.

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