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Review: The potential of freshwater eels (*Anguilla* spp.) as a source of medicine and food

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Abstract. *Arifiandita DM, Ramadhan FA, Paramita FS, Purnamassari F, Sholiqin M, Naim DMd, Setyawan AD. 2025. Review: The potential of freshwater eels (*Anguilla *spp.) as a source of medicine and food. Asian J Nat Prod Biochem 23: 52-69.* Freshwater eels (*Anguilla* spp.) possess exceptional nutritional and pharmacological properties that position them as a promising yet underutilized resource for functional foods and biomedicine. This review synthesizes current knowledge of their taxonomy, ecology, and life history traits, linking these to their biochemical composition and health benefits. Eel tissues are rich in high-quality proteins, long-chain omega-3 fatty acids (EPA and DHA), fat-soluble vitamins (A, D, E), and unique bioactive compounds such as glycosaminoglycans, peptides, and antimicrobial proteins. These constituents contribute to antioxidant, anti-inflammatory, immunomodulatory, anticoagulant, cardiovascular, and antimicrobial effects, with additional potential in neuroprotection, reproductive health, and skin repair. Comparative data across species and environments reveal substantial variability in nutrient profiles influenced by taxonomy, life stage, and habitat. The review also explores traditional and modern processing techniques that affect nutrient retention and bioavailability and discusses emerging applications in pharmaceuticals, nutraceuticals, and cosmetics. Recognizing the ecological threats to wild eel populations, the paper emphasizes the crucial role of sustainable utilization strategies, including aquaculture and value-added product development, in ensuring the conservation of this valuable resource. By integrating biological, nutritional, medicinal, and cultural perspectives, this review provides a comprehensive foundation for future research and innovation in eel-based health products.

Keywords: *Anguilla*, bioactive compounds, functional food, pharmacological properties, omega-3 fatty acids

INTRODUCTION

Wetlands are vital ecosystems that support biodiversity, regulate hydrological cycles, and provide numerous ecosystem services essential to both environmental sustainability and human livelihoods (Nygren and Lounela 2023). These areas, which include swamps, marshes, peatlands, and mangroves, play a key role in climate regulation, water purification, and the provision of habitat for aquatic and terrestrial species (Novita et al. 2022). Among the many resources offered by wetlands, freshwater eels (*Anguilla* spp.) stand out due to their ecological significance and economic potential.

Freshwater eels belong to the genus *Anguilla* within the family Anguillidae, and they are unique for their catadromous life cycle spawning occurs in the ocean. In contrast, most of their growth phase occurs in freshwater or estuarine environments (Arai 2020). This complex migratory behavior connects marine and freshwater ecosystems, highlighting their ecological importance. The genus comprises 19 species distributed across tropical, subtropical, and temperate regions (Froese and Pauly 2022), with species such as *Anguilla japonica* Temminck and Schlegel 1846, *Anguilla marmorata* Quoy and Gaimard 1824, *Anguilla bicolor* McClelland 1844, *Anguilla rostrata* Lesueur 1817, and *Anguilla anguilla* Linnaeus 1758 showing varied adaptations to local environmental conditions (Arai and Abdul Kadir 2017).

Unfortunately, freshwater eel populations are experiencing dramatic declines due to a combination of overfishing, habitat destruction, pollution, and barriers to migration, such as dams and waterway modifications (Pike et al. 2020; Boubee et al. 2022). The European eel (*A. anguilla*), for instance, is currently listed as Critically Endangered by the IUCN Red List, while other species are also showing signs of stress (Moura et al. 2022). The decline in eel populations has raised significant concerns not only for ecological stability but also for communities that depend on eels for food, culture, and income (Chowdhury et al. 2020).

Despite increasing attention to their conservation status and aquaculture development, scientific studies on the medicinal and nutritional applications of freshwater eels remain limited and fragmented (Sila et al. 2018; Chowdhury et al. 2020). At the same time, eel ecology and biology are relatively well-documented (Arai 2016; Pike et al. 2020), but integrated reviews that bridge taxonomy, nutritional science, and pharmacological potential are still lacking (Santos et al. 2018; Lee et al. 2019). Given the global momentum toward functional foods, natural therapeutics, and sustainable aquatic bioresources, a more comprehensive understanding of *Anguilla* spp. is urgently needed. This review aims to address these gaps and encourage further interdisciplinary research on their value as food and medicine (Rajasekaran et al. 2018; Rana et al. 2019).

In traditional medicine systems across Asia and parts of Europe, freshwater eels have long been used to treat ailments ranging from arthritis to skin conditions, reflecting a longstanding ethnomedicinal knowledge base (Kumar et al. 2017; Rajasekaran et al. 2018). In Japan, for instance, eel consumption is associated with health and vitality, particularly during the summer months. Meanwhile, in Indonesia, various ethnic communities use eel-based products as tonics or treatments for fatigue and joint pain (Wijayanti et al. 2018). However, scientific validation and consolidation of these traditional practices into structured biomedical frameworks remain limited.

With the growing global interest in functional foods and natural product-based pharmaceuticals, freshwater eels present a valuable yet underutilized resource. Their diverse species, wide distribution, and rich bioactive profile make them ideal candidates for further research and development in food and medicine. Nonetheless, unlocking their full potential requires an integrative understanding that encompasses taxonomy, physiology, ecology, nutritional composition, ethnomedicine, and sustainable harvesting and processing techniques.

This review aims to fill that gap by synthesizing available knowledge on the biological, nutritional, and pharmacological characteristics of freshwater eels. It highlights the interconnections between their life history traits and biochemical composition, evaluates their use in traditional and modern health applications, and explores opportunities and challenges for their sustainable utilization. Emphasis is placed on identifying species with the highest potential, understanding how environmental factors influence their nutrient content, and exploring innovative processing methods that preserve or enhance their medicinal properties.

Ultimately, this review aims to provide a scientific basis for future research and policy development on the responsible use of freshwater eels as a source of food and medicine. Hence, it contributes to the broader goals of food security, biodiversity conservation, and health promotion, particularly in regions where eel populations are integral to local ecosystems and cultures.

BIOLOGICAL CHARACTERISTICS RELEVANT TO NUTRITIONAL AND MEDICINAL USE

Taxonomy and distribution

The genus *Anguilla* comprises 19 recognized species and subspecies of catadromous freshwater eels that are globally distributed from tropical to temperate zones (Froese and Pauly 2022) (Table 1). These species are generally divided into tropical and temperate groups based on biogeographic range and habitat preference. Tropical species include *Anguilla marmorata* Quoy and Gaimard 1824, *Anguilla bicolor* subsp. *bicolor*, *Anguilla bicolor* subsp. *pacifica*, *Anguilla celebesensis* Kaup, 1856, and *Anguilla megastoma* Kaup 1856, predominantly found in Southeast Asia, Oceania, and parts of Africa. Temperate species, such as *Anguilla anguilla* Linnaeus 1758 (European eel), *Anguilla rostrata* Lesueur 1817 (American eel), and *Anguilla japonica* (Japanese eel), are common in Europe, North America, and East Asia (Tzeng et al. 2003; Arai 2016).

These eels share a unique catadromous life history it is born in the sea, migrate to freshwater to grow, and return to the ocean to spawn. Despite similarities in the life cycle, *Anguilla* species have diversified significantly in morphology, genetics, and environmental tolerances, with distribution patterns strongly influenced by spawning sites, oceanic currents, and continental hydrology (Minegishi et al. 2005; Tsukamoto 2009). For example, *A. japonica* spawns in the western Pacific near the Mariana Ridge, and its larvae are transported via the Kuroshio Current to East Asian coasts (Tsukamoto et al. 2011). Similarly, *A. anguilla* originates in the Sargasso Sea and disperses across the North Atlantic to European inland waters (Pike et al. 2020).

From an evolutionary perspective, the Indo-Pacific region is hypothesized as the center of origin and radiation for the *Anguilla* genus (Arai and Chino 2012). This is supported by fossil records and molecular phylogenetic studies, which show a greater species richness and genetic divergence in tropical eels from this region (Minegishi et al. 2005). The existence of basal lineages such as *Anguilla borneensis* Popta 1924 and *Anguilla luzonensis* Watanabe, Aoyama and Tsukamoto 2009 reinforces the theory of tropical origin followed by dispersal to temperate zones through oceanic gyres and continental drift (Shiao et al. 2002).

The habitat range of *Anguilla* spp. is highly diverse. These eels are found in freshwater rivers, lakes, estuaries, brackish lagoons, and coastal wetlands. Some species, such as *A. marmorata* and *A. bicolor*, exhibit extraordinary ecological plasticity, capable of withstanding wide fluctuations in salinity, temperature, and oxygen levels. Studies in Indonesia and the Philippines have documented *A. marmorata* thriving in tidal swamps and mangrove fringes, environments characterized by high environmental stress and frequent salinity shifts (Arai and Abdul Kadir 2017). This adaptability has been linked to molecular and physiological traits, such as efficient osmoregulatory systems, respiratory plasticity, and antioxidant enzyme expression (Li et al. 2015; Wang et al. 2016).

Species distribution is not only a function of oceanic transport and habitat availability but is also influenced by competition, predation, and anthropogenic pressures. In regions with multiple co-occurring *Anguilla* species, niche partitioning is evident through habitat depth preferences, diel movement patterns, and dietary composition (Jellyman and Tsukamoto 2010). For instance, in the tropical rivers of Sulawesi and Sumatra, *A. celebesensis* tends to occupy upstream segments, while *A. marmorata* dominates lowland and estuarine zones (Kautsari et al. 2023). Such differentiation allows coexistence and may reflect underlying physiological specializations that affect not only habitat use but also tissue composition and nutrient accumulation.

Table 1. Overview of the 19 recognized species of genus *Anguilla*, their morphological traits, habitats, and distribution

Species name	Key morphological traits	Primary habitat	Geographic distribution	Reference
A. anguilla	Smaller head, narrow snout	Rivers, lakes	Europe, North Africa	Pike et al. (2020)
A. australis australis	Small eyes, blunt snout	Freshwater streams	Southeastern Australia, Tasmania	Arai (2022)
A. australis schmidtii	Variant of *A. australis*, minor color differences	Rivers	New Zealand	Arai (2022)
A. bengalensis bengalensis	Long dorsal fin, blunt snout	Rivers, swamps	Indian subcontinent	Kumar et al. (2017)
A. bengalensis labiata	Prominent lips, larger pectoral fins	Rivers	Sri Lanka, Southern India	Froese and Pauly (2022)
A. bicolor bicolor	Dark dorsal stripe, yellow belly	Rivers, lowland wetlands	Indian Ocean basin (South Asia, Indonesia)	Fahmi (2015)
A. bicolor pacifica	Lighter belly, elongated body	Coastal rivers, estuaries	Southeast Asia, Melanesia	Cabral et al. (2016)
A. borneensis	Fewer vertebrae, short dorsal fin	Blackwater rivers	Borneo	Fahmi (2015)
A. celebesensis	Short snout, blunt head	Highland rivers	Sulawesi, Java, Sumatra	Kautsari et al. (2023)
A. dieffenbachii	Large, robust body	Large rivers	New Zealand	Tesch (2003)
A. interioris	Small eyes, fewer vertebrae	Highland streams	Papua New Guinea	Froese and Pauly (2022)
A. japonica	Large eye, silvering during migration	Rivers, estuaries	East Asia (Japan, Korea, China)	Tsukamoto et al. (2011)
A. luzonensis	Distinct lateral line scales	Rivers	Luzon Island, Philippines	Minegishi et al. (2005)
A. marmorata	Marbled skin pattern, large size	Tropical rivers, brackish estuaries	Indo-Pacific, Indian Ocean, East Africa	Arai and Abdul Kadir (2017)
A. megastoma	Large mouth, deep body	Brackish lakes	Polynesia, Micronesia	Shiao et al. (2002)
A. mossambica	Uniform dark coloration	Coastal rivers	East Africa, Madagascar	Arai (2016)
A. obscura	Slender body, short fins	Estuaries, lowland rivers	Papua New Guinea, Fiji	Tesch (2003)
A. reinhardtii	Long body, distinct dorsal fin base	Rivers	Eastern Australia	Jellyman and Tsukamoto (2010)
A. rostrata	Slightly deeper body, pigmented leptocephalus	Coastal rivers, lakes	Eastern North America	Tesch (2003)

The nutritional and medicinal potential of freshwater eels is closely linked to their taxonomy and biogeography. Tropical eels such as *A. bicolor pacifica* and *A. marmorata* have been shown to exhibit higher fat reserves and distinct fatty acid profiles compared to temperate species, likely due to differences in water temperature, metabolic demands, and dietary availability (Ahn et al. 2015; Zhang et al. 2018). Moreover, regional variation in habitat types ranging from oligotrophic mountain streams to eutrophic wetlands can shape microbial exposure and immune responses in eels, potentially affecting the bioactive compounds found in their mucus and internal organs (Hilles et al. 2019; Chowdhury et al. 2020).

The decline in *Anguilla* populations, especially *A. anguilla*, has become a conservation concern globally. Overfishing, dam construction, and pollution have fragmented migration routes and reduced suitable habitats, leading to IUCN listings of several species as endangered or critically endangered (Pike et al. 2020). These pressures disproportionately affect temperate species with more defined and narrow migratory corridors. On the other hand, tropical species, due to their ecological flexibility and wider spawning seasons, may offer more resilient alternatives for aquaculture and resource utilization (Arai 2022).

Understanding species-specific distribution patterns and environmental requirements is essential for the sustainable exploitation of eels for food and medicinal purposes. Identifying populations with high natural lipid and protein content, as well as those adapted to controlled environments, can guide selective breeding programs and targeted harvesting. Moreover, the characterization of the biochemical and genetic diversity within the genus *Anguilla* holds the potential for the discovery of novel compounds with therapeutic properties, such as glycosaminoglycans, peptides, and antioxidants, a prospect that is both intriguing and exciting (Sila et al. 2018; Bote et al. 2024).

In conclusion, the taxonomy and distribution of *Anguilla* spp. form the biological foundation for their significant roles in the application of food and medicinal industries. Their global distribution, physiological plasticity, and ecological versatility not only ensure wide availability but also contribute to their compositional richness. A comprehensive understanding of these aspects is, therefore, critical for effective conservation, aquaculture development, and bioresource utilization.

Morphology and physiology

The morphology of *Anguilla* spp. is characterized by a streamlined, elongated body that facilitates benthic locomotion and migration across varying aquatic environments. These eels typically exhibit a scaleless or minutely scaled integument that is enveloped in a thick mucous layer. This unique and significant adaptation plays a vital role in protection against pathogens and assists in cutaneous respiration (Chowdhury et al. 2020). One of the most notable external features is the presence of a single continuous fin that merges the dorsal, caudal, and anal fins, allowing for sinuous, efficient swimming even in narrow crevices or low-flow aquatic systems (Tesch 2003). Pectoral fins are reduced in size, aiding their burrowing and substrate-associated behavior. The body coloration varies depending on species and developmental stage, ranging from transparent in the glass eel phase to dark green or yellowish-brown in adult yellow eels and eventually silvery in mature migrating eels (Righton et al. 2016).

Internal morphology reflects numerous physiological specializations. The musculature of *Anguilla* is highly developed and serves not only for locomotion but also as a major site of energy storage, particularly in the form of lipids during the yellow eel stage (Saito et al. 2015). Lipid content in muscle and liver increases significantly in preparation for the silver eel phase, which is marked by sexual maturation and long-distance migration to oceanic spawning grounds. These lipid reserves are critical, as the eels cease feeding once migration begins, relying solely on stored energy (Damsteegt et al. 2015).

Physiologically, freshwater eels are remarkably tolerant of environmental stressors such as salinity shifts, hypoxia, and temperature variation. A range of biochemical and molecular adaptations supports these tolerances. For instance, *A. marmorata* has been shown to upregulate antioxidant enzymes such as manganese superoxide dismutase (MnSOD) and copper-zinc superoxide dismutase (Cu/ZnSOD) in response to salinity changes, indicating a strong oxidative stress management system (Wang et al. 2016). Similarly, the expression of ion-regulating proteins like the vacuolar-type H^+-ATPase (VHAB1) in the gills of *A. marmorata* increases under brackish and marine conditions, facilitating osmoregulation during habitat transitions (Li et al. 2015).

Another vital organ with physiological and nutritional significance is the corpuscle of Stannius (CS), a gland unique to fish and located near the kidney. In eels, the CS secretes stanniocalcin, a hormone responsible for regulating calcium and phosphate levels in the blood, thus playing a role in bone formation and ionic homeostasis (Gu et al. 2015). This regulatory function is crucial not only for the eel's survival in different ionic environments but also suggests that tissues influenced by CS activity may possess mineral-rich biochemical profiles relevant to dietary health.

The swim bladder is another notable anatomical feature. In *Anguilla* spp., the swim bladder is physoclistous, meaning it is not connected to the digestive tract, and its gas content is regulated via the rete mirabile. This complex capillary system enables countercurrent gas exchange. This structure is supported by a gas gland that releases lactic acid and CO_2 to facilitate oxygen diffusion into the swim bladder lumen (Pelster et al. 2016). Importantly, the swim bladder tissue is rich in collagen and glycoproteins, compounds that have applications in nutraceuticals and cosmetics due to their role in skin elasticity and joint health (Caruso et al. 2020; Bote et al. 2024).

Hormonal control is also integral to eel physiology, particularly during the transition from yellow to silver eels. Endocrine changes include increases in gonadotropins and thyroid hormones that mediate gonadal development, metabolic regulation, and secondary sexual characteristics (Tzeng et al. 2003). These hormonal changes are also linked to shifts in muscle composition, where concentrations of Omega-3 Polyunsaturated Fatty Acids (PUFAs), especially Eicosapentaenoic Acid (EPA) and Docosahexaenoic Acid (DHA), increase significantly. These fatty acids are essential for human cardiovascular and neurological health and are a major reason why eel meat is valued as a functional food (Rana et al. 2019; Lee et al. 2019).

Additionally, the mucosal system of eels has garnered attention due to its antimicrobial and immunological properties. The mucus, secreted by goblet cells in the skin, contains a mixture of peptides, glycoproteins, and immunoglobulins that help protect against microbial invasion (Hilles et al. 2019). Some of these bioactive components have shown potential antibacterial effects against human pathogens, suggesting potential applications in the development of natural antibiotics or probiotic supplements (Rajasekaran et al. 2018).

Overall, the morphological and physiological features of *Anguilla* spp. underscore the species' ability to thrive in diverse and often harsh aquatic environments. More importantly, these characteristics directly contribute to the accumulation of bioactive compounds in their tissues, including omega-3 fatty acids, collagen, peptides, and essential minerals. These compounds not only support the survival and reproductive success of eels but also offer substantial nutritional and medicinal value for human consumption. Therefore, a deeper understanding of eel biology is essential to guide sustainable harvesting practices and optimize their utilization in health-related industries.

NUTRITIONAL COMPOSITION AND VARIABILITY

Macronutrients and micronutrients

Freshwater eels (*Anguilla* spp.) are considered nutritionally dense fish due to their high-quality protein and fat content. The protein content typically ranges between 15 to 20 g per 100 g of raw edible portion, depending on species and maturity stage (Ahn et al. 2015; Zhang et al. 2018). These proteins are easily digestible and possess a complete amino acid profile, including all essential amino acids required for human nutrition. The biological value of eel protein is considered comparable to that of eggs and milk, making it suitable for populations with limited access to conventional animal protein sources (Rana et al. 2019). Moreover, the relatively low collagen-to-muscle protein ratio enhances the meat's tenderness and palatability.

Fat content in eel meat is another notable attribute, with concentrations ranging from 5 to 15 g per 100 g depending on species, seasonality, diet, and physiological state (Saito et al. 2015). Tropical species such as *A. bicolor* and *A.*

marmorata have been reported to accumulate more intramuscular fat than temperate species, likely due to warmer aquatic environments and different energy storage patterns (Lee et al. 2019). This lipid fraction is particularly valuable as it contains a high proportion of long-chain omega-3 polyunsaturated fatty acids (PUFAs), notably eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids play well-established roles in cardiovascular protection, anti-inflammatory response, and brain development, contributing to the growing interest in eels as a functional food (Raatz et al. 2013; Calder 2015). The omega-3 to omega-6 ratio in eel fat is generally favorable, supporting anti-thrombotic and anti-atherogenic effects.

In addition to high-fat content, eel tissues also contain significant levels of phospholipids and sterols. Phospholipids contribute to membrane fluidity and cellular signaling, while cholesterol and related sterols serve as precursors for steroid hormones and bile acids (Caruso et al. 2020). In silver eels preparing for oceanic migration, lipid profiles shift to optimize energy availability and buoyancy control, which also influences the composition of edible tissues (Damsteegt et al. 2015). These dynamic changes in fat composition during life stages may impact the nutritional quality of harvested eels and should be considered in aquaculture or wild harvest strategies.

Eel meat is also rich in various essential micronutrients. Among minerals, phosphorus and calcium are present in relatively high concentrations, supporting bone development and energy metabolism (FAO 2021). Iron content in eel meat can reach up to 2.5 mg per 100 g, contributing to hemoglobin synthesis and oxygen transport (Lee et al. 2019). Other trace minerals such as magnesium, zinc, and selenium are also abundant, providing antioxidant protection, enzymatic cofactor functions, and immune support (Sila et al. 2018). Selenium, in particular, is notable for its synergistic role with vitamin E in preventing cellular oxidative damage.

The vitamin profile of freshwater eels includes lipophilic vitamins A, D, and E, along with several water-soluble B-complex vitamins. Vitamin A (retinol) is important for vision, epithelial maintenance, and immune competence, and its content in the eel liver is especially high, often exceeding that found in cod liver oil (Caruso et al. 2020). Vitamin D, primarily in the form of cholecalciferol (D_3), supports calcium absorption and bone health, making eels a valuable dietary source, particularly for populations at risk of deficiency. Vitamin E (tocopherol) functions as a major lipid-soluble antioxidant, helping to stabilize polyunsaturated fatty acids and prevent lipid peroxidation (Raatz et al. 2013). B-complex vitamins such as B_{12}, B_6, niacin, and riboflavin play crucial roles in energy metabolism and nervous system function.

Notably, the micronutrient composition of eels varies not only by species but also by environmental conditions and diet. Farmed eels fed formulated feeds enriched with fish oil and vitamin premixes tend to exhibit higher fat-soluble vitamin levels compared to wild-caught counterparts (Ahn et al. 2015). However, wild eels may accumulate more trace elements from natural diets, which could offer additional health benefits or, conversely, pose risks due to bioaccumulation of contaminants such as mercury or Polychlorinated Biphenyls (PCBs) in polluted habitats (van den Heuvel et al. 2008). Therefore, understanding the source and condition of eels is crucial for maximizing nutritional benefits and minimizing potential hazards.

The high concentration of functional nutrients in eels makes them particularly suitable for vulnerable groups such as children, elderly populations, and individuals with high nutritional needs. Furthermore, the soft texture of eel meat and its savory flavor profile enhance its acceptability across cultures, supporting its traditional and modern culinary uses (FAO 2021). In many Asian countries, particularly Japan, China, and Indonesia, eel-based dishes such as *unagi kabayaki* or grilled *ikan sidat* are prized not only for taste but also for perceived health benefits, including stamina and recovery support (Tsukamoto 2009).

The increasing consumer demand for nutrient-dense and bioactive-rich foods offers opportunities to promote freshwater eels as a valuable component of healthy diets. However, sustainable sourcing, aquaculture optimization, and processing techniques must be refined to ensure the long-term viability of this resource. Comparative studies on species-specific nutrient profiles, seasonal variation, and the effects of cooking and preservation methods would further inform strategies to enhance eel-based food products. Further research on the nutritional composition of *Anguilla* spp. can help bridge the gap between traditional knowledge and evidence-based dietary recommendations.

Nutritional differences across species and environment

The nutritional profile of *Anguilla* spp. is not uniform across species or environments. Variability in fat, protein, mineral, and vitamin content has been documented based on differences in species, habitat conditions, feeding habits, sex, and life stage (Ahn et al. 2015; Zhang et al. 2018). For instance, *A. japonica* reared in intensive aquaculture systems tends to accumulate more intramuscular fat compared to wild-caught counterparts, largely due to energy-rich formulated feeds and restricted swimming space (Saito et al. 2015). Conversely, wild eels often display leaner muscle but may have higher micronutrient diversity derived from natural diets and varied aquatic environments (FAO 2021). These differences have implications for both food quality and health benefits derived from consumption.

Species-specific variation is especially evident in tropical vs. temperate eels. Tropical species such as *A. marmorata* and *A. bicolor* tend to exhibit higher lipid deposition and distinctive fatty acid profiles, which may be influenced by ambient water temperature and metabolic adaptation to warmer climates (Lee et al. 2019). *A. mossambica* from African rivers, for instance, exhibits lower protein-to-fat ratios than *A. anguilla* from colder European waters, possibly reflecting different energy storage strategies (Arai 2016). These patterns are important when selecting eel species for targeted nutritional formulations or functional food applications. Differences in growth rate, metabolic rate, and diet type between species further amplify compositional diversity in eel meat.

Environmental conditions such as water salinity, temperature, and mineral composition also affect eel nutrient profiles. Studies on *A. bicolor pacifica* have shown that individuals from brackish environments possess higher ash and mineral content, especially calcium and magnesium, compared to those from freshwater rivers, likely due to differential ion availability in the water (Kautsari et al. 2023). Water quality factors, including pollution and dissolved oxygen, can also influence oxidative stress in eels, potentially altering antioxidant enzyme levels and associated nutrient markers (Wang et al. 2016). Thus, both natural and anthropogenic environmental variability must be considered when evaluating eel nutritional content.

Sexual dimorphism can further contribute to nutritional differences. Female eels often grow larger and store more lipids than males, particularly during the yellow and silver eel stages, when energy is reserved for reproductive migration (Righton et al. 2016). These differences are driven by the intricate hormonal regulation of metabolism and gonadal development, which not only affect total fat content but also influence the profile of bioactive lipids such as omega-3 fatty acids (Sila et al. 2018). In aquaculture settings, sex-related growth patterns may be manipulated through hormonal or environmental interventions to improve yield and nutritional output.

Life stage is another critical determinant of nutritional composition in *Anguilla* spp, during the transition from yellow eel to silver eel a process known as *silvering* profound physiological changes occur, including elevated fat accumulation, increased muscle mass, and enhanced antioxidant defenses (Tesch 2003). These changes prepare the eel for long-distance migration and reproductive success but also affect the quality of the meat harvested at this stage. Silver eels generally contain more DHA and EPA, along with higher levels of energy reserves, making them particularly valuable for both food and medicinal purposes (Ahn et al. 2015). However, post-spawning individuals exhibit depleted nutrient levels due to the energetic cost of migration and gametogenesis.

Regional variation in nutrition has also been noted across eel populations, even within the same species. For example, *A. bicolor* collected from different Indonesian rivers exhibits varying levels of zinc, selenium, and vitamin E, likely reflecting differences in local water chemistry and dietary sources (Kautsari et al. 2023). This intra-species variation poses challenges for the standardization of eel-based products, especially when used for health supplements or traditional medicine. Identifying and controlling for regional factors is essential for ensuring consistent product quality in commercial eel harvesting and processing.

Farming practices introduce another layer of variability. Eels raised under controlled aquaculture systems often receive high-protein diets supplemented with omega-3-rich fish oils and vitamin premixes, which may improve the nutritional quality of the meat (Rana et al. 2019). However, confinement may limit physical activity and alter muscle structure, leading to differences in textural quality and fat distribution. On the other hand, semi-intensive or extensive systems that mimic natural environments may produce leaner eels with potentially richer micronutrient profiles but lower overall yield. Balancing these trade-offs is critical for sustainable and health-oriented eel production.

Understanding how species identity, life history stage, and environmental context influence the biochemical composition of eels is vital for optimizing their use in both food and pharmaceutical applications. These factors must be carefully accounted for in aquaculture protocols, wild harvesting practices, and regulatory frameworks governing food safety and nutritional labeling. Further research focusing on molecular and metabolomic profiling across species and habitats may reveal biomarkers associated with specific health benefits. This knowledge would greatly enhance the capacity to develop standardized, high-value eel-derived products for local and international markets.

PHARMACOLOGICAL AND MEDICINAL POTENTIAL

Anti-inflammatory and immune-modulating properties

Freshwater eels (*Anguilla* spp.) are emerging as a promising source of bioactive compounds with notable anti-inflammatory and immune-regulating effects (Table 2). Among these, protein hydrolysates and peptides generated through enzymatic processing have been shown to modulate inflammatory pathways by inhibiting the production of key pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6) (Sila et al. 2018). These cytokines play central roles in the development of chronic inflammatory diseases, including arthritis, inflammatory bowel disease, and asthma. The ability of eel-derived peptides to downregulate these mediators suggests therapeutic potential for managing low-grade systemic inflammation and improving immune resilience.

In addition to cytokine modulation, eel peptides have demonstrated the capacity to inhibit pro-inflammatory enzymes such as Cyclooxygenase-2 (COX-2) and inducible Nitric Oxide Synthase (iNOS). These enzymes are responsible for generating inflammatory prostaglandins and nitric oxide, respectively, both of which contribute to pain, swelling, and tissue degradation (Park et al. 2017). Eel peptides can act at the transcriptional level, reducing gene expression of COX-2 and iNOS in activated immune cells such as macrophages and dendritic cells. This dual inhibition approach is valuable for attenuating both the initiation and amplification of inflammatory responses, thereby providing a broader anti-inflammatory effect compared to single-target agents. The potential of eel peptides to broaden the scope of anti-inflammatory effects is an intriguing area of research that could open up new possibilities for treating inflammatory conditions.

Table 2. Summary on *Anguilla* spp. (freshwater eels) chemical constituents, pharmacological properties, and medical utilization

Name	Chemical constituents	Pharmacological properties	Traditional medical utilization	Modern medical utilization	References
A. anguilla	GAGs, collagen, retinol, EPA, DHA	Anticoagulant, neuroprotective, anti-aging	Joint and nerve tonic	GAG-based anticoagulant, skin repair supplement	Arai (2016); Caruso et al. (2020); Bote et al. (2024)
A. bicolor	PUFA-rich oil, selenium, vitamin B complex	Anti-inflammatory, immunomodulatory	General health tonic	Peptide-based immune boosters, anti-inflammatory supplements	Ahn et al. (2015); Sila et al. (2018)
A. bicolor pacifica	PUFA, vitamins A & D, collagen	Antioxidant, skin repair	Used as a vitality enhancer	Functional food ingredient	Lee et al. (2019)
A. celebesensis	Calcium, vitamin D, peptides, collagen	Bone health, antibacterial	Postpartum recovery aid	Collagen supplements, antimicrobial peptides	Rajasekaran et al. (2018)
A. japonica	EPA, DHA, vitamin A & E, peptides, collagen	Cardiovascular, antioxidant, anti-inflammatory	Energy and stamina tonic	Functional foods, nutraceuticals, cosmetics	Sila et al. (2018); Lee et al. (2019)
A. marmorata	GAGs, peptides, vitamin D, minerals	Antimicrobial, anticoagulant, tissue repair	Wound treatment, vitality	GAG-extracts, topical antimicrobials	Chowdhury et al. (2020); Zhu et al. (2020)
A. megastoma	MUFAs, mucins, amino acids	Mucosal protection, fertility-enhancing	Aphrodisiac, energy enhancement	Fertility supplements	Arai (2016)
A. mossambica	Proteins, peptides	Antibacterial, antioxidant	Local medicine for infections	Topical wound-healing candidate	Arai (2016); Chowdhury et al. (2020)
A. rostrata	Omega-3 and -6, Zn, P, amino acids	Lipid-lowering, hepatoprotective	Liver tonic	Cardiovascular formulations	Calder (2015); Lee et al. (2019)

Note: The remaining species were categorized as *limited data*, *unknown*, or *unexplored* due to insufficient information.

Apart from peptides, eel tissues also contain immunomodulatory polysaccharides such as β-glucans and mannans, which are predominantly found in the mucus and connective tissues. These compounds stimulate immune responses in a balanced manner, enhancing host defense against pathogens while preventing hyperactivation that can lead to autoimmune disorders (Chowdhury et al. 2020). β-glucans are known to bind to pattern recognition receptors such as Dectin-1 and Toll-like receptors (TLRs), triggering signaling cascades that activate macrophages, natural killer cells, and neutrophils (Rajasekaran et al. 2018). Mannan, a polysaccharide composed of mannose units, may also support tissue regeneration and anti-inflammatory activity by modulating T-cell responses and promoting regulatory cytokine production.

The relevance of these bioactive components extends to clinical conditions characterized by chronic inflammation and immune dysregulation. For example, animal models of rheumatoid arthritis have shown significant reductions in joint swelling and cartilage erosion following oral or injectable administration of eel protein hydrolysates (Bote et al. 2024). Similar benefits have been observed in models of allergic airway inflammation, where eel-derived compounds reduced eosinophil infiltration, mucus hypersecretion, and airway hyperresponsiveness. These findings suggest potential applications of eel-based ingredients in managing asthma, atopic dermatitis, and other hypersensitivity-related disorders.

In the context of autoimmune diseases, where the immune system attacks its own tissues, modulation of T-cell activity is crucial. Eel peptides have demonstrated potential in promoting regulatory T-cell (Treg) populations while suppressing pro-inflammatory Th1 and Th17 cells, which are implicated in conditions such as multiple sclerosis, psoriasis, and inflammatory bowel disease (Sila et al. 2018). By shifting the immune balance toward tolerance and controlled inflammation, these compounds may offer a complementary approach to conventional immunosuppressants with fewer adverse effects. The capacity to induce a more regulated immune state is particularly relevant for chronic, relapsing conditions that require long-term management.

Bioavailability and delivery also play key roles in the effectiveness of these compounds. Studies indicate that low-molecular-weight peptides derived from eel muscle are more readily absorbed in the gastrointestinal tract, reaching systemic circulation and target tissues efficiently (Zhu et al. 2020). Additionally, encapsulation technologies such as liposomes and hydrogels are being explored to enhance stability and controlled release of eel bioactives in immune-modulating supplements. These delivery systems not only improve efficacy but also broaden the range of formulations for consumer use, including capsules, powders, and functional beverages.

It is also important to consider the synergy between different classes of eel-derived compounds. For instance, combining peptides with polysaccharides may offer additive or even synergistic effects on immune modulation, as each targets different components of the immune cascade. Peptides may primarily influence cytokine production and enzyme activity, while polysaccharides engage innate immune receptors and modulate cellular activation. Formulating products that incorporate both components could result in broader-spectrum immune support suitable for a wide range of inflammatory and autoimmune disorders.

From a safety perspective, eel-derived compounds have generally demonstrated low toxicity and good tolerability in experimental studies. Unlike synthetic anti-inflammatory drugs, which often carry risks of gastrointestinal, renal, or cardiovascular side effects, bioactive peptides and polysaccharides from eels act through natural signaling mechanisms and are less likely to disrupt homeostatic functions (Calder 2015). Nevertheless, rigorous toxicological and allergenicity testing is essential before these compounds can be fully approved for use in pharmaceuticals or functional foods.

The potential of freshwater eels as a source of anti-inflammatory and immune-modulating agents represents a valuable convergence of traditional use and modern biomedical research. As chronic inflammation and immune-related disorders continue to rise globally, eel-derived bioactives may offer accessible, natural alternatives to synthetic therapeutics. Continued research, particularly clinical trials and mechanistic studies, will be key in validating these benefits and translating them into safe, effective, and market-ready health solutions.

Antioxidant activities

Freshwater eels (*Anguilla* spp.) are an excellent source of naturally occurring antioxidant compounds that protect biological tissues from oxidative damage. These compounds include Polyunsaturated Fatty Acids (PUFAs), particularly Eicosapentaenoic Acid (EPA) and Docosahexaenoic Acid (DHA), as well as vitamins A and E, and various endogenous peptides (Calder 2015; Lee et al. 2019). Antioxidants play a vital role in maintaining cellular homeostasis by neutralizing free radicals and Reactive Oxygen Species (ROS) that are implicated in aging, cancer development, cardiovascular disease, and neurodegenerative disorders (Raatz et al. 2013). Eel tissues, especially muscle and liver, are rich in these bioactives, contributing to their long-standing use in both food and traditional medicine to promote vitality and prevent disease.

The antioxidant capacity of eel-derived peptides is of particular interest due to their multifunctional roles. Protein hydrolysates produced through the enzymatic digestion of eel muscle yield low-molecular-weight peptides that exhibit strong radical scavenging activity in vitro, as measured by DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid) assays (Sila et al. 2018). These peptides function by donating hydrogen atoms to unstable molecules, chelating metal ions, and inhibiting lipid peroxidation. Their amino acid composition particularly the presence of hydrophobic and aromatic residues like tyrosine, histidine, and methionine contributes to their high antioxidant potential (Zhu et al. 2020). Such peptides are being explored for use in functional foods, dietary supplements, and even topical formulations targeting oxidative stress-related conditions.

Vitamin E (α-tocopherol), another key component of eel tissues, is a lipid-soluble antioxidant that protects cellular membranes from oxidative damage by scavenging lipid peroxyl radicals. It is particularly abundant in the muscle fat of tropical eel species such as *A. marmorata* and *A. bicolor pacifica*, which tend to accumulate more intramuscular lipids than temperate species (Ahn et al. 2015). In addition to preserving membrane integrity, vitamin E plays a role in gene expression regulation and modulation of immune responses. Similarly, vitamin A (retinol and its derivatives), found in high concentrations in eel liver, supports epithelial health and neutralizes singlet oxygen and peroxyl radicals, making it valuable for skin repair, immune modulation, and ocular health (Caruso et al. 2020). These vitamins, when consumed through eel products, contribute to the prevention of oxidative stress-associated diseases.

Lipid fractions extracted from eel tissues also display protective effects against oxidative stress in biological systems. EPA and DHA have been found to reduce oxidative markers and improve antioxidant enzyme activities, such as Superoxide Dismutase (SOD), catalase, and glutathione peroxidase, in animal models (Calder 2015). These omega-3 fatty acids are incorporated into cell membranes, where they modulate membrane fluidity and influence redox signaling pathways. Moreover, their metabolism leads to the formation of resolvins and protectins, lipid mediators that not only reduce inflammation but also enhance cellular defense mechanisms against oxidative injury. This dual action of PUFAs antioxidant and anti-inflammatory strengthens the therapeutic potential of eel oil in chronic disease prevention.

The commercial formulation *Eelax*, derived from eel extracts, exemplifies the application of these antioxidant principles in health product development. Although limited peer-reviewed studies are available on *Eelax*, preliminary reports and in vitro analyses suggest it reduces oxidative damage in human dermal fibroblasts and promotes collagen production, supporting claims related to anti-aging and skin repair (Bote et al. 2024). The efficacy is likely due to the synergistic interaction of eel peptides, collagen, and unsaturated fatty acids. Other formulations, especially in East Asian markets, incorporate eel-derived antioxidants into capsules, functional drinks, and cosmeceutical products aimed at combating fatigue, promoting skin elasticity, and supporting heart health.

Advances in processing technologies such as enzymatic hydrolysis and nanoencapsulation have further improved the stability and delivery of eel-based antioxidants. Nanoencapsulated eel oil has demonstrated improved resistance to oxidation during storage and better absorption in gastrointestinal models compared to non-encapsulated forms (Rajasekaran et al. 2018). These technologies are especially relevant for preserving the bioactivity of PUFAs and peptides, which are otherwise prone to degradation during conventional processing. The integration of such techniques into product development pipelines enhances the feasibility of commercial antioxidant-rich eel products with extended shelf life and higher functional efficacy.

The bioavailability of eel-derived antioxidants is also a critical factor in determining their physiological effects. Studies have shown that peptides smaller than 3 kDa exhibit greater intestinal absorption and stronger antioxidant effects in cellular assays (Sila et al. 2018). Likewise, fat-soluble vitamins and omega-3s are better absorbed when consumed with dietary fats conditions naturally met in eel meat, which is rich in endogenous lipids. This intrinsic nutritional synergy allows for more efficient nutrient absorption and utilization, especially when eel is consumed as a whole food or minimally processed product.

Overall, the antioxidant properties of freshwater eels are supported by a diverse array of bioactive compounds that act through complementary mechanisms. Since oxidative stress is a common pathological feature in many chronic diseases, eel-derived antioxidants offer promising avenues for both preventive and therapeutic nutrition. Their continued study and development into validated products may contribute significantly to modern strategies in health maintenance, aging, and disease management.

Lipid regulation and cardiovascular health

Freshwater eels (*Anguilla* spp.) are an abundant natural source of long-chain Omega-3 Polyunsaturated Fatty Acids (PUFAs), particularly Eicosapentaenoic Acid (EPA) and Docosahexaenoic Acid (DHA), which have well-documented effects on cardiovascular health. These fatty acids are primarily found in eel muscle and liver, contributing significantly to their lipid profile and biological value (Lee et al. 2019). Unlike saturated fats, omega-3 PUFAs exert protective roles in the cardiovascular system by modulating lipid metabolism, reducing blood triglycerides, and improving overall cholesterol balance. Regular consumption of EPA and DHA is associated with lowered Low-Density Lipoprotein (LDL) cholesterol and elevated High-Density Lipoprotein (HDL) cholesterol, thus promoting a healthier lipid profile (Calder 2015). This balance is essential in reducing the risk of atherosclerosis and coronary artery disease.

EPA and DHA also influence blood pressure regulation through several interrelated mechanisms. These fatty acids enhance the production of Nitric Oxide (NO), a vasodilator that relaxes blood vessel walls and improves endothelial function (Raatz et al. 2013). Additionally, they reduce the synthesis of pro-inflammatory eicosanoids such as thromboxane A2 and leukotrienes, which are involved in vasoconstriction and platelet aggregation (Calder 2015). By reducing vascular inflammation and oxidative stress, eel-derived omega-3s improve vascular elasticity and lower systolic and diastolic blood pressure. Clinical and preclinical studies have confirmed that diets enriched with EPA and DHA can lead to modest but consistent reductions in blood pressure, particularly in individuals with hypertension (Kris-Etherton et al. 2002).

The anti-inflammatory properties of EPA and DHA are central to their cardiovascular benefits. Chronic low-grade inflammation plays a key role in the initiation and progression of atherosclerosis, leading to plaque formation and hardening of the arteries. Omega-3 derived from eel modulates inflammatory signaling by downregulating nuclear factor-kappa B (NF-κB) activity and reducing circulating levels of C-Reactive Protein (CRP), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α) (Sila et al. 2018). This results in reduced leukocyte adhesion to endothelial cells and reduced macrophage infiltration into the arterial wall, thereby reducing the likelihood of plaque rupture and thrombosis. These effects highlight the potential role of eel fat in not only preventing but also attenuating the progression of existing cardiovascular disorders.

Beyond their systemic effects, EPA and DHA have been shown to alter lipid metabolism at the molecular level. They activate peroxisome proliferator-activated receptors (PPARs), particularly PPAR-α, which regulate the expression of genes involved in lipid oxidation and energy homeostasis (Calder 2015). This activation leads to increased fatty acid β-oxidation in the liver and reduced synthesis of triglycerides and Very Low-Density Lipoproteins (VLDL). These effects contribute to the lowering of circulating triglyceride levels, a key factor in metabolic syndrome and cardiovascular risk. In eel-fed animal models, reductions in hepatic fat accumulation and plasma triglycerides have been observed, providing experimental support for these lipid-lowering actions (Ahn et al. 2015).

The lipid composition of eel provides an additional advantage due to its favorable omega-3 to omega-6 ratio. Modern diets often contain excessive amounts of omega-6 fatty acids, which can trigger inflammatory pathways if not balanced with adequate omega-3 intake. Eel-derived oils offer a natural way to restore this balance, potentially reducing the risk of endothelial dysfunction, thrombosis, and arterial inflammation (Lee et al. 2019). This nutritional profile makes eel an appealing candidate for dietary intervention strategies aimed at improving cardiovascular health, particularly in aging populations or those at risk of metabolic disease.

Recent product development has begun incorporating eel oil into functional food formats and dietary supplements targeting heart health. In East Asian markets, soft-gel capsules containing purified eel oil enriched with EPA and DHA are marketed for supporting blood pressure regulation, cholesterol control, and cognitive function (Bote et al. 2024). Some formulations also include additional antioxidants such as vitamin E or coenzyme Q10 to enhance vascular protection further. Although consumer uptake is still modest compared to fish oil from anchovy or sardine, eel oil offers unique cultural, nutritional, and biochemical attributes that distinguish it within the omega-3 supplement space.

Processing and preservation methods significantly affect the stability and bioactivity of eel-derived lipids. Omega-3 fatty acids are prone to oxidation when exposed to heat, light, or oxygen, resulting in off-flavors and reduced efficacy. Technologies such as vacuum-sealing, refrigeration, and nanoencapsulation have been employed to enhance shelf life and preserve functional integrity during storage (Rajasekaran et al. 2018). Flash freezing and microencapsulation of eel oil, in particular, have shown promising results in protecting PUFAs and ensuring consistent delivery of active compounds in supplement and food applications. These methods are vital for translating the cardiovascular benefits of eel-derived lipids into accessible, high-quality health products.

Eel-based sources of EPA and DHA offer an effective and culturally relevant means of addressing the growing burden of cardiovascular diseases worldwide. Their ability to modulate blood lipids, improve endothelial function, and reduce inflammatory responses positions them as valuable ingredients for dietary strategies and therapeutic interventions. Future clinical studies and long-term population data will be important in fully validating their role and optimizing formulation and dosage. As part of a balanced diet and integrated health approach, eel-derived lipids have the potential to have a significant impact on public health outcomes related to heart disease and metabolic dysfunction.

Anticoagulant effects

Glycosaminoglycans (GAGs), a class of linear polysaccharides found abundantly in animal connective tissues, have been identified in significant quantities within the skin and swim bladder of freshwater eels (*Anguilla* spp.), particularly the European eel (*A. anguilla*). These compounds, including dermatan sulfate and heparan sulfate, are structurally similar to pharmaceutical heparin and possess the ability to modulate blood coagulation pathways (Caruso et al. 2020). The anticoagulant action of eel-derived GAGs is mediated through their interaction with antithrombin III, a serine protease inhibitor that deactivates clotting factors such as thrombin and factor Xa. This mechanism prolongs clotting times and effectively reduces the risk of thrombosis, a major contributor to stroke, myocardial infarction, and venous thromboembolism (Zhu et al. 2020).

Unlike synthetic or mammalian-derived heparin, eel-based GAGs have demonstrated a promising safety profile. Studies have shown that these compounds inhibit coagulation without inducing hemolysis or triggering Heparin-Induced Thrombocytopenia (HIT), a serious side effect of conventional heparin therapy (Bote et al. 2024). This lack of hemolytic activity makes eel-derived anticoagulants an attractive alternative, especially for patients with heparin sensitivity or those requiring long-term anticoagulation. In vitro assays have confirmed that glycosaminoglycans from eel extracts can extend activated Partial Thromboplastin Time (aPTT) and Prothrombin Time (PT), both critical indicators of anticoagulant activity (Rajasekaran et al. 2018). These properties align with therapeutic goals in preventing clot formation without impairing platelet function or causing excessive bleeding, addressing the needs of heparin-sensitive patients, and fostering a sense of empathy and consideration in the audience.

The high concentration of GAGs in eel skin is associated with their role in maintaining tissue hydration, elasticity, and protection. These molecules are composed of repeating disaccharide units, often sulfated, that carry a negative charge and bind to positively charged proteins and ions in blood plasma (Chowdhury et al. 2020). These interactions are key to their anticoagulant properties, as the sulfation pattern, particularly 2-O and 6-O sulfation, determines binding affinity to antithrombin and other regulatory proteins. The structural complexity of eel-derived GAGs may offer opportunities to fine-tune anticoagulant activity through purification and modification, potentially leading to more targeted therapies with reduced side effects.

Recent advances in enzymatic extraction and purification techniques have facilitated the isolation of bioactive GAGs from eel tissues in sufficient purity and yield for pharmaceutical evaluation. These methods typically involve protease digestion, ethanol precipitation, and ion-exchange chromatography to concentrate the anticoagulant fractions while removing contaminants and non-sulfated polysaccharides (Sila et al. 2018). Structural characterization using techniques such as Nuclear Magnetic Resonance (NMR) and mass spectrometry has confirmed the similarity of eel GAGs to low molecular weight heparins, though with distinct bioactive profiles. These methods also enable standardization, a key requirement for clinical development and regulatory approval.

Beyond their anticoagulant function, eel-derived GAGs may provide ancillary benefits in vascular protection and tissue healing. Their interaction with growth factors and adhesion molecules supports endothelial integrity and may reduce vascular inflammation (Calder 2015). These effects are particularly valuable in post-thrombotic care or as adjuvants to cardiovascular therapies. In animal models, administration of purified GAGs from eel extracts has led to reduced thrombus formation without impairing wound healing or triggering immune responses. However, it's important to note that there may be potential risks or limitations associated with their use, such as allergic reactions or immune system responses. These promising findings suggest broader applications for eel-derived compounds in integrative cardiovascular care, possibly in combination with other natural or synthetic agents.

It is important to note that the development of eel-based anticoagulants must consider ethical, ecological, and sustainability concerns. The European eel (*A. anguilla*) is classified as critically endangered due to overfishing and habitat loss (Pike et al. 2020). Therefore, sourcing GAGs from this species must be conducted responsibly, ideally from aquaculture or by utilizing byproducts of fish processing to minimize waste. Exploring alternative species with similar biochemical properties, such as *A. marmorata* or *A. bicolor*, may reduce pressure on vulnerable populations while expanding the resource base for drug development (Arai 2016). However, the real reassurance comes from the potential of eel aquaculture systems with controlled breeding and closed-loop production that could support sustainable access to raw materials for pharmaceutical applications.

From a regulatory perspective, further toxicological studies and human clinical trials are necessary before eel-derived GAGs can be approved as anticoagulant agents. Although preliminary research supports their efficacy and safety, long-term data on pharmacokinetics, immunogenicity, and dose standardization are needed. Additionally, interactions with other anticoagulant drugs and possible contraindications must be assessed in diverse patient populations. Collaboration between biomedical researchers, pharmacologists, and regulatory agencies will be essential to guide the transition from laboratory research to clinical application.

Eel-derived glycosaminoglycans represent a compelling natural source of anticoagulant agents with distinct advantages over existing therapies. Their biochemical structure, multifunctional health effects, and relatively low toxicity profile position them as strong candidates for novel drug development. Continued innovations in extraction, purification, and formulation will likely accelerate their integration into pharmaceutical pipelines focused on cardiovascular and thrombotic disorders.

Antibacterial and antibiotic potential

Freshwater eels (*Anguilla* spp.) possess an innate defense system that includes a complex and biologically active mucus layer, which serves as a frontline barrier against microbial invasion. This mucus is rich in Antimicrobial Peptides (AMPs), lysozymes, proteases, and immunoglobulin-like proteins that collectively function to prevent bacterial colonization and infection (Chowdhury et al. 2020). These bioactive molecules are secreted in response to physical stress or environmental pathogens and are particularly concentrated along the skin and gill surfaces. AMPs from eel mucus typically exhibit cationic properties, allowing them to interact with negatively charged bacterial membranes, resulting in membrane disruption and cell death (Rajasekaran et al. 2018). Their spectrum of activity includes Gram-positive and Gram-negative bacteria, suggesting their potential as natural alternatives to synthetic antibiotics.

Several studies have confirmed the antibacterial efficacy of eel mucus extracts against clinically relevant pathogens. For instance, in vitro assays have shown that mucus-derived peptides from *A. japonica* and *A. marmorata* inhibit the growth of *Streptococcus mutans*, *Staphylococcus aureus*, and *Escherichia coli* (Bote et al. 2024). These effects are dose-dependent and occur at relatively low concentrations, supporting their use as biocompatible antimicrobial agents. In addition to killing planktonic bacteria, eel mucus peptides have been reported to disrupt bacterial biofilms, which are typically resistant to conventional antibiotics. This characteristic makes eel-derived AMPs particularly promising for applications in oral care products, wound healing formulations, and surface disinfectants.

The mechanism of action for eel AMPs involves both physical and biochemical pathways. Beyond membrane disruption, some peptides enter bacterial cells and interfere with DNA replication, protein synthesis, or metabolic enzyme function. Others act by chelating essential metal ions or modulating host immune responses to support bacterial clearance (Chowdhury et al. 2020). Unlike traditional antibiotics, which often target specific metabolic pathways and are prone to resistance development, AMPs exert multi-targeted effects, reducing the risk of microbial adaptation. Their structural flexibility also allows for modifications that enhance stability, activity, or selectivity for specific pathogens.

In the context of aquaculture, particularly in Japanese eel farming (*A. japonica*), controlled use of antibiotics remains a subject of ongoing research. Pharmacokinetic studies of antibiotics such as amoxicillin in eels have revealed insights into absorption, distribution, metabolism, and excretion patterns unique to this species (Ahn et al. 2015). These studies help determine appropriate dosage regimes, withdrawal periods, and residue limits to ensure both therapeutic efficacy and consumer safety. However, overuse or misuse of antibiotics in aquaculture poses serious risks, including the development of antibiotic-resistant bacteria and contamination of aquatic ecosystems (FAO 2021). Therefore, integrating natural antimicrobial compounds such as eel AMPs into aquaculture management could reduce antibiotic reliance and support sustainable disease control.

The potential of eel mucus as a source of novel antibiotic agents is being explored in pharmaceutical research. Using modern extraction and purification techniques, such as ultrafiltration, reversed-phase chromatography, and mass spectrometry, researchers have been able to isolate and characterize individual peptides with potent antibacterial activity (Zhu et al. 2020). Some of these peptides share structural motifs with known antimicrobial families like defensins and cathelicidins, while others represent novel peptide classes. In experimental models, purified eel AMPs have demonstrated synergistic effects when combined with conventional antibiotics, lowering the Minimum Inhibitory Concentrations (MICs) required for pathogen inhibition and potentially mitigating resistance development.

Beyond antibacterial action, eel mucus peptides may exert immunomodulatory effects that enhance host defense mechanisms. By stimulating macrophage activation, cytokine secretion, and epithelial barrier function, these compounds contribute to a holistic antimicrobial defense system (Sila et al. 2018). This dual role of direct antimicrobial activity and immune enhancement positions eel mucus as a multifunctional bioresource with applications extending into immunotherapy, vaccine adjuvants, and antimicrobial coatings for medical devices. Moreover, topical formulations containing eel-derived peptides may be effective for treating skin infections or preventing microbial colonization in wounds and burns.

Despite their potential, challenges remain in developing eel-derived antibacterial agents for clinical and commercial use. Stability under physiological conditions, especially against protease degradation, is a key issue that must be addressed through peptide modification or encapsulation strategies. Additionally, large-scale production of AMPs from eel mucus is currently limited by low yields and extraction efficiency. Biotechnological approaches, such as recombinant peptide expression or synthetic peptide libraries, are being investigated to overcome these limitations and scale up production sustainably (Park et al. 2017). Regulatory pathways for the approval of AMP-based products must also be clarified, particularly regarding toxicity, allergenicity, and environmental impact.

The unique antimicrobial properties of eel mucus offer a compelling natural solution to rising concerns over antibiotic resistance and biofilm-related infections. With continued investment in extraction, characterization, and delivery technologies, eel-derived AMPs may soon play a role in the next generation of antimicrobial therapies. Their integration into aquaculture, food preservation, personal care, and clinical medicine reflects the broader applicability of natural peptides in addressing microbial threats across sectors.

Additional bioactivities

Beyond their widely studied antioxidant, anti-inflammatory, and cardiovascular properties, eel (*Anguilla* spp.) extracts exhibit a range of additional bioactivities with potential therapeutic applications. Among these are immunostimulatory, analgesic, reproductive, and neuroprotective effects, many of which are supported by the complex biochemical makeup of eel tissues. Eel-derived peptides, amino acids, and lipid fractions are thought to interact with physiological pathways that regulate immune function, pain perception, hormonal activity, and neural processes (Sila et al. 2018; Lee et al. 2019). Although research on these aspects is relatively nascent compared to mainstream pharmaceutical agents, the preliminary evidence offers strong justification for further exploration and development.

Immunostimulatory activity has been reported in various eel-derived compounds, particularly protein hydrolysates that enhance innate immune responses. Eel peptides have demonstrated the capacity to activate macrophages and natural killer (NK) cells, increase phagocytic activity, and stimulate the release of cytokines such as interleukin-10 (IL-10) and interferon-gamma (IFN-γ) (Zhu et al. 2020). These actions contribute to the enhancement of the host's non-specific immunity and may be beneficial in preventing infections, especially in immunocompromised individuals. Additionally, glycoproteins and mucins in eel mucus are believed to contribute to mucosal immune defense by promoting epithelial barrier function and limiting pathogen entry (Chowdhury et al. 2020). As interest grows in functional foods and natural immunomodulators, these compounds may serve as safe, food-derived alternatives to synthetic immune boosters.

Eel extracts have also shown potential in modulating pain and promoting analgesic effects. Although this property is less well-documented than others, studies using protein hydrolysates have reported reduced behavioral responses to noxious stimuli in animal models, suggesting antinociceptive activity (Rajasekaran et al. 2018). The mechanism is thought to involve modulation of inflammatory mediators and opioid-like pathways, although the exact peptides responsible remain to be fully characterized. Bioactive lipids, including DHA, may also contribute by altering membrane fluidity in neuronal cells and dampening neural transmission of pain signals (Calder

2015). This opens the possibility of developing eel-derived nutraceuticals or topical preparations for managing mild to moderate pain or inflammatory discomfort.

The reproductive health potential of eels is another area gaining scientific interest, particularly due to lipid and amino acid profile changes across their life cycle stages. During the silvering phase, when eels prepare for long-distance migration and reproduction, there is a notable shift in lipid metabolism and hormone levels, including increased accumulation of steroid precursors such as cholesterol and polyunsaturated fatty acids (Arai 2016; Righton et al. 2016). These compounds are essential for gonadal development and gamete maturation, and their concentrations suggest a biological alignment with reproductive function. Extracts from mature eel tissues may support fertility and hormone regulation, particularly in populations experiencing reproductive disorders associated with inflammation, oxidative stress, or hormonal imbalance. Some preliminary reports have even proposed eel oil as a supportive agent for testosterone balance and ovarian function, though human trials are lacking.

In addition to reproductive health, eel-derived compounds show promise in supporting neurological function. DHA, one of the dominant fatty acids in eel fat, plays a critical role in brain development, synaptic plasticity, and cognitive performance. It supports neuronal membrane integrity, modulates neurotransmitter activity, and exhibits neuroprotective effects by reducing neuroinflammation and oxidative damage (Raatz et al. 2013). Peptides with antioxidant and anti-inflammatory activities may also contribute to the prevention or delay of neurodegenerative conditions such as Alzheimer's and Parkinson’s disease. Furthermore, the presence of bioactive amino acids such as tryptophan and tyrosine, which serve as precursors for serotonin and dopamine, indicates a potential role in mood regulation and stress response (Sila et al. 2018). These biochemical attributes align with growing interest in nutrition-based strategies for mental health support.

The multifunctional nature of eel bioactive compounds suggests that synergistic interactions between multiple compounds may enhance their overall efficacy. For instance, combinations of lipids, peptides, and trace elements such as zinc and selenium both present in significant quantities in eel tissues may collectively promote immune, endocrine, and neurological health (Lee et al. 2019). Such synergies could be harnessed in the design of integrated functional formulations that simultaneously target multiple physiological systems. This integrative potential aligns well with modern health paradigms that emphasize holistic, systems-level approaches to disease prevention and wellness maintenance.

While many of these additional bioactivities remain underexplored, they offer valuable directions for future research and innovation. Rigorous clinical trials and bioavailability studies are needed to validate the health effects of eel-derived compounds in human populations. Additionally, sustainable sourcing practices and standardized extraction protocols must be developed to ensure consistent product quality and ethical use of eel resources. As scientific and consumer interest in multifunctional marine-derived bioactive compounds grows, freshwater eels may increasingly serve as the basis for next-generation functional foods and therapeutic agents targeting diverse health domains.

TRADITIONAL AND MODERN PROCESSING TECHNIQUES

Traditional practices

Traditional knowledge and culinary practices surrounding freshwater eels (*Anguilla* spp.) are deeply rooted in various cultures across Asia, Europe, and Africa. These practices reflect not only culinary preferences but also the need for preservation, given the perishable nature of eel meat and the seasonal availability of wild eels. Traditional methods emphasize flavor enhancement, texture modification, and microbiological safety without the use of modern refrigeration or synthetic additives (FAO 2021). Across cultures, eel preparation is often intertwined with ritual, identity, and medicinal beliefs, further elevating its value beyond mere sustenance.

In Indonesia, freshwater eels commonly referred to as *ikan sidat* are processed through several traditional techniques, including sun-drying, smoking, fermentation, and spice-rich cooking. One notable preparation is *rendang belut*, a regional variant of the Minangkabau dish *rendang*. Eel meat is simmered with coconut milk and a blend of spices until dry and darkened in color (Fahmi 2015). This method imparts antimicrobial properties due to the presence of turmeric, galangal, garlic, and chili, and also significantly extends the product’s shelf life. In other parts of Indonesia, eels are sun-dried and salted, then fried or boiled before consumption practices that support rural preservation needs and facilitate transportation to urban markets (Arai 2016).

Japanese eel cuisine, particularly the dish *unagi kabayaki*, is among the most globally recognized eel preparations. The method involves filleting the eel, skewering it, and grilling it over charcoal while basting it with a sweet soy-based sauce made from mirin, soy sauce, and sugar (Tsukamoto 2009). This cooking process enhances umami flavor and produces a glossy caramelized exterior while maintaining the soft texture of the eel meat. Traditionally consumed during midsummer, *unagi* is believed to restore stamina and vitality, making it both a culinary delicacy and a seasonal health food (Lee et al. 2019). The cultural reverence for eel in Japan has also led to the development of refined culinary tools and preservation techniques, including vacuum-sealing and refrigeration for commercial *unagi* products.

In European countries such as the Netherlands, Germany, and the United Kingdom, eels are traditionally smoked or pickled. Smoking often involves hardwoods like oak or alder, which infuse the eel flesh with deep, earthy flavors while reducing moisture content and inhibiting microbial growth (Tesch 2003). Pickled eels are typically prepared in a vinegar brine infused with bay leaves, mustard seeds, and black pepper, offering both preservation and palatability. In parts of Scandinavia, smoked eel is served as part of festive dishes, paired with rye bread or creamy sauces, reflecting its place in traditional gastronomy (Pike et al. 2020). These European practices often focus on enhancing flavor complexity and extending shelf stability, especially in coastal and riverine regions with strong fishing traditions.

In the Philippines, freshwater eels are commonly grilled, fried, or used in sour stews like *sinigang*, where tamarind-based broth helps tenderize the meat and neutralize its natural oiliness (Arai and Chino 2012). In some regions of Mindanao, eels are cooked in coconut milk with ginger and turmeric, reflecting the integration of local spices and indigenous techniques. Meanwhile, in Papua New Guinea and parts of Melanesia, *A. megastoma* and other native species are wrapped in banana leaves and baked in earthen ovens alongside root crops, illustrating low-tech but effective methods for flavor infusion and nutritional retention (Froese and Pauly 2022). These traditional methods are not only adapted to the local ecology but also often involve social cooperation and cultural transmission.

In African countries such as Madagascar and Mozambique, *A. mossambica* is caught using handmade traps and often grilled over open fires or stewed with local herbs. Smoking is also practiced in some fishing communities, especially in areas with poor access to refrigeration. Although less documented in scientific literature, these traditional practices are essential in sustaining rural protein sources and preserving biodiversity-related knowledge (Arai 2016). Moreover, the use of eel in folk medicine—as a tonic or restorative food remains embedded in oral traditions and community health beliefs.

Traditional processing methods can also affect the nutritional and medicinal properties of eels. Smoking and grilling may result in some loss of water-soluble vitamins, such as B-complex groups, but tend to preserve or even concentrate fat-soluble components like vitamin D and omega-3 fatty acids (Lee et al. 2019). Spice-rich preparations like *rendang* or *sinigang* may provide synergistic antioxidant and anti-inflammatory benefits through the combined action of eel lipids and botanical compounds (Sila et al. 2018). These practices, while developed in response to environmental and cultural contexts, align well with current functional food principles and require urgent further biochemical evaluation.

The continuity of traditional eel processing practices demonstrates a strong link between cultural heritage and food system resilience. These methods have evolved over generations to balance taste, preservation, and health, offering insights for modern product development and sustainable resource use. With growing interest in culinary biodiversity and ethnogastronomy, documenting and integrating traditional eel processing knowledge may contribute to food security strategies and smallholder economic development. The urgency of sustained interdisciplinary research is clear, as it can support innovation that honors tradition while enhancing food safety and nutritional outcomes.

Modern innovations

Technological advancements in food science and biotechnology have opened new possibilities for processing and utilizing freshwater eels (*Anguilla* spp.) in more efficient, hygienic, and nutritionally optimized ways. Traditional methods, while valuable for cultural and practical reasons, often result in nutrient loss and limited shelf life. Modern innovations such as vacuum-sealing and flash freezing allow for the preservation of eel freshness and nutritional integrity during storage and distribution (FAO 2021). Vacuum-sealing helps prevent oxidative rancidity of omega-3 fatty acids, while flash freezing at ultra-low temperatures minimizes microbial growth and structural degradation. These technologies are essential for expanding eel export markets and ensuring safety in ready-to-eat products.

Ultrasound-assisted and microwave-assisted cooking methods have also been applied to improve the processing of eel meat. These techniques offer rapid and uniform heat transfer, reducing cooking time while preserving sensitive nutrients like vitamin A, vitamin E, and long-chain polyunsaturated fatty acids (Zhu et al. 2020). Additionally, ultrasound can enhance marination efficiency and meat tenderness by disrupting muscle fiber structure, making it useful in value-added eel products such as flavored fillets or jerky. Microwave cooking, on the other hand, enables energy-efficient heating and reduces the formation of undesirable compounds such as heterocyclic amines or polycyclic aromatic hydrocarbons compared to open-fire grilling (Lee et al. 2019). The integration of these methods can lead to healthier and more palatable eel-based food products.

A growing area of innovation involves the enzymatic hydrolysis of eel tissues to extract bioactive peptides. Controlled hydrolysis using enzymes such as pepsin, trypsin, or alcalase can release low-molecular-weight peptides with proven bioactivities, including antioxidant, anti-inflammatory, and antihypertensive effects (Park et al. 2017; Sila et al. 2018). These peptides can be incorporated into functional foods, beverages, or encapsulated supplements. Advanced purification methods such as ultrafiltration, ion-exchange chromatography, and reverse-phase HPLC are used to isolate specific peptides for research and product formulation. Optimization of hydrolysis conditions pH, temperature, time, and enzyme specificity—has become a key focus in maximizing bioactivity and yield.

In the cosmetics industry, eel skin and swim bladder have emerged as valuable sources of marine collagen. Collagen extracted from eel tissues shows high solubility, low viscosity, and favorable amino acid composition rich in glycine, proline, and hydroxyproline, all of which contribute to skin elasticity and repair (Caruso et al. 2020). Compared to bovine or porcine collagen, marine collagen from eel sources offers better absorption and lower allergenic potential, making it suitable for topical and oral applications. It is now used in a variety of cosmetic products, including anti-aging creams, sheet masks, and collagen supplements, particularly in East Asian markets where marine-derived ingredients are culturally favored (Bote et al. 2024). The trend is further supported by consumer demand for clean-label, animal-free, and sustainable beauty solutions.

Another promising innovation is nanoencapsulation, which enables the delivery of bioactive compounds from eel extracts in targeted and protected formats. Nanoemulsions, liposomes, and biopolymer-based nanoparticles are being developed to improve the stability, solubility, and bioavailability of sensitive compounds like omega-3 fatty acids and peptides (Rajasekaran et al. 2018). This technology is particularly valuable in functional food and pharmaceutical sectors, where dosage control, taste masking, and prolonged release are crucial. Preliminary studies have shown that nanoencapsulated eel oil retains its bioactivity longer and is more efficiently absorbed in gastrointestinal models compared to non-encapsulated oil (Zhu et al. 2020). With further optimization, nanoencapsulation could enhance the efficacy of eel-derived products and facilitate their integration into complex formulations.

Modern packaging innovations also support the commercialization of eel-based products. Modified atmosphere packaging (MAP) and smart packaging systems with freshness indicators can help maintain product quality and inform consumers about storage conditions (FAO 2021). For instance, packaging eel fillets with nitrogen or carbon dioxide atmospheres reduces lipid oxidation and bacterial growth, thereby extending shelf life without chemical preservatives. In countries like Japan and South Korea, eel bento boxes with microwave-safe, vacuum-sealed compartments are now widely sold in convenience stores and online platforms, demonstrating the synergy of processing and packaging technologies.

Sustainability has also become a focus in modern eel processing innovations. With wild eel populations under threat, aquaculture systems have been developed to meet increasing demand without further depleting natural stocks. Intensive eel farming now utilizes Recirculating Aquaculture Systems (RAS) that control water quality, feeding, and growth conditions, resulting in standardized and traceable products (Arai 2022). These systems facilitate the production of high-quality raw material for modern processing while minimizing environmental impact. The combination of controlled aquaculture and precision processing strengthens the entire value chain for eel-based health and food products.

Collectively, these innovations demonstrate how traditional resources like freshwater eels can be elevated through science-driven approaches. The integration of advanced processing, extraction, and packaging technologies not only enhances product quality but also ensures safety, functionality, and consumer appeal. As research and development in this field continue to grow, freshwater eels are increasingly positioned as a valuable resource in modern food, health, and cosmetic industries.

Nutrient retention and bioavailability

Processing methods play a significant role in determining the nutritional quality and bioactivity of eel-based products. The thermal sensitivity of certain nutrients, particularly omega-3 Polyunsaturated Fatty Acids (PUFAs), antioxidants, and bioactive peptides, requires careful consideration during preparation. Among various cooking techniques, frying has been shown to cause the greatest loss of PUFAs due to oxidation and high-temperature degradation (Raatz et al. 2013). In contrast, gentler methods such as steaming and grilling at controlled temperatures tend to preserve omega-3 content and maintain antioxidant integrity (Zhu et al. 2020). These findings emphasize the importance of processing optimization for retaining the functional properties of eel nutrients.

Steaming and grilling also contribute to the preservation of water-soluble vitamins such as B-complex and vitamin C, which are otherwise prone to leaching and thermal destruction during boiling or deep-frying (FAO 2021). Studies comparing cooking methods have found that grilled eel retains higher levels of vitamin E and antioxidant enzymes compared to fried or microwaved samples (Lee et al. 2019). Furthermore, controlled grilling, as practiced in traditional Japanese *unagi kabayaki*, can result in a favorable flavor profile while minimizing nutrient loss. The Maillard reaction, which occurs during grilling, may also contribute to the formation of flavor-enhancing peptides and melanoidins with antioxidant properties (Sila et al. 2018). These combined effects reinforce the value of culturally informed yet nutritionally sound processing methods.

Marinating is another technique that has gained attention due to its dual role in enhancing and preserving flavor. The use of acidic or spiced marinades, such as those incorporating vinegar, citrus juice, turmeric, garlic, and chili, has been found to inhibit microbial growth while maintaining the integrity of key nutrients (Fahmi 2015). In eel processing, marinating not only improves palatability but can also enhance the shelf life without requiring synthetic preservatives. When paired with low-heat cooking methods or drying, marinating helps retain essential micronutrients like iron and zinc, as well as thermolabile compounds such as certain peptides and vitamins (Chowdhury et al. 2020). This makes marinated eel products suitable for both local consumption and value-added export markets.

Bioavailability, defined as the proportion of nutrients that are absorbed and utilized by the body, is influenced by both the intrinsic properties of eel tissues and the methods used for preparation. For instance, lipid-soluble nutrients such as vitamins A, D, and E show improved bioavailability when consumed with dietary fats, which are naturally present in eel meat (Calder 2015). However, excessive processing may denature protein structures or oxidize lipids, thereby reducing their digestibility and absorption efficiency (Park et al. 2017). Enzymatic hydrolysis, on the other hand, can improve peptide bioavailability by breaking down large proteins into absorbable fragments, a strategy often employed in functional food and supplement development (Sila et al. 2018). This illustrates the potential synergy between processing technology and nutrient delivery.

Micronutrient retention also varies with storage and reheating practices. For example, repeated heating of eel dishes can degrade heat-sensitive compounds, including selenium-dependent enzymes and vitamin C. Packaging innovations such as vacuum-sealing and Modified Atmosphere Packaging (MAP) can help prevent oxidative degradation and preserve nutrient integrity during storage (FAO 2021). Additionally, the inclusion of natural antioxidants such as rosemary extract or tocopherols during processing has been shown to stabilize PUFA-rich oils in eel products, enhancing shelf stability and consumer safety (Caruso et al. 2020). These strategies collectively support the production of health-oriented eel products with extended usability.

Understanding the relationship between processing and nutrient dynamics is essential for product development, especially in the context of health claims and regulatory approval. For eel-based products marketed as functional foods, standardization of processing protocols is needed to ensure consistency in nutrient profiles and bioactive concentrations. This includes monitoring cooking time, temperature, pH, and the use of additives, all of which affect chemical composition and sensory properties (Lee et al. 2019). Digestibility and bioavailability studies using in vitro and in vivo models can provide further information for formulation strategies, ensuring that nutrients reach their intended physiological targets.

There is also growing interest in combining traditional and modern approaches to optimize nutrient retention. For example, integrating marination with vacuum-cooking (sous-vide) techniques can preserve thermosensitive nutrients while enhancing tenderness and flavor. Such hybrid methods draw on ethnogastronomic knowledge while applying scientific principles to control thermal exposure and oxygen contact (Zhu et al. 2020). These innovations are particularly relevant for high-value eel products aimed at premium health markets, where nutritional quality is a key differentiator.

Maintaining the functional value of eel nutrients requires an interdisciplinary understanding of food science, biochemistry, and culinary practice. As consumer interest in functional foods continues to grow, eel-based products must meet expectations not only for taste and convenience but also for scientifically validated health benefits. Advances in analytical methods, such as metabolomics and nutrient tracking, provide powerful tools to support this goal. Continued collaboration between researchers, processors, and traditional food practitioners can ensure that nutrient-rich eel products remain effective and culturally relevant across markets.

CHALLENGES AND FUTURE PERSPECTIVES

Despite the growing interest in the nutritional and medicinal potential of freshwater eels (*Anguilla* spp.), several challenges hinder their full utilization and sustainable commercialization. One of the most pressing issues is the declining wild eel populations, particularly in temperate species such as *A. anguilla* and *A. japonica*, which are now listed as critically endangered and endangered, respectively, by the IUCN (Pike et al. 2020). Overfishing, habitat loss, pollution, and barriers to migration, such as dams, have severely disrupted their life cycles (Tsukamoto 2009). Conservation efforts are often complicated by the limited understanding of eel spawning behavior and migration routes in the open ocean, which makes population recovery strategies difficult to implement (Arai 2016).

Aquaculture offers a potential solution to reduce pressure on wild populations, yet it presents its own set of limitations. Eel farming is still largely reliant on wild-caught glass eels for seed stock, as artificial breeding in captivity has not yet been commercialized on a wide scale (FAO 2021). This dependence perpetuates the depletion of juvenile eel populations and creates bottlenecks in supply chains. In addition, intensive eel aquaculture requires high energy input, controlled water quality, and fishmeal-based feed, raising concerns about environmental sustainability and cost-effectiveness (Arai 2022). Research into captive breeding techniques, including hormonal induction and larval rearing, is progressing but remains technically and economically challenging.

Another significant challenge lies in standardizing the quality and safety of eel-based food and health products. Variability in species, habitat, diet, and life stage leads to inconsistent nutrient profiles, which complicates product formulation and quality control (Zhang et al. 2018). Moreover, eels are susceptible to bioaccumulation of environmental contaminants such as mercury, dioxins, and Polychlorinated Biphenyls (PCBs), especially in polluted waters (van den Heuvel et al. 2008). These substances pose health risks to consumers and complicate efforts to gain regulatory approval for eel-derived nutraceuticals and food ingredients. Ensuring traceability, implementing contaminant monitoring, and promoting clean aquaculture environments are necessary to mitigate these concerns.

From a processing standpoint, balancing nutrient retention with microbial safety remains a complex task. While modern technologies such as vacuum-sealing, enzymatic hydrolysis, and nanoencapsulation enhance product functionality and shelf life, their adoption requires investment in infrastructure, skilled personnel, and consumer education (Caruso et al. 2020) traditional methods. However, culturally significant, often lack standardization and fail to meet international food safety standards. Bridging the gap between traditional knowledge and modern technology is essential to ensure that eel-based products are both safe and accessible to a broad market.

Market development for eel-based functional products also faces cultural and perceptual barriers. In some regions, eels are perceived as exotic, oily, or unappetizing, limiting their acceptance among consumers unfamiliar with their culinary or medicinal value (Fahmi 2015). Furthermore, the premium price of eel products driven by limited supply, labor-intensive preparation, and processing costs may restrict access for lower-income populations. Marketing strategies must therefore focus not only on health claims but also on taste appeal, cultural storytelling, and culinary versatility to broaden consumer acceptance.

In the scientific research field, strong clinical evidence is still needed to support the health benefits of eel-derived compounds. While in vitro and animal studies have shown promising antioxidant, anti-inflammatory, antimicrobial, and cardiovascular effects, human trials are still limited in scope and scale (Park et al. 2017; Sila et al. 2018). Regulatory agencies require comprehensive toxicological data, pharmacokinetics, and efficacy evaluations before allowing health claims on functional foods or supplements. Investment in interdisciplinary research that connects food science, pharmacology, and nutrition will be essential to translating preliminary findings into validated applications.

Moving forward, there are several opportunities to enhance the role of freshwater eels in nutrition, medicine, and sustainable food systems. Advances in biotechnology including molecular breeding, omics technologies, and synthetic biology could accelerate the domestication and scale-up of eel strains for aquaculture (Arai 2022). Precision aquaculture techniques using AI and sensor-based monitoring may improve the efficiency, welfare, and environmental performance of eel farms. Additionally, the development of plant- or microbial-based alternatives to fishmeal can improve the sustainability of eel diets without compromising their nutritional outcomes.

Policy support and international collaboration are also crucial for the long-term sustainability of eel resources. Harmonized regulations across countries on eel harvesting, trade, and aquaculture practices would improve transparency and conservation outcomes. Programs that integrate traditional ecological knowledge with scientific data, particularly in Southeast Asia, where eels play a role in local diets and medicine, could foster community-based management and benefit-sharing. Supporting smallholder farmer engagement and value-added processing may also contribute to rural development and food sovereignty.

With coordinated efforts in research, policy, industry, and community engagement, freshwater eels have the potential to become a sustainable and functional resource for future food and health innovation. Their unique combination of nutritional richness, pharmacological potential, and cultural heritage offers a compelling case for continued investment and responsible development.

CONCLUDING REMARKS

Freshwater eels (*Anguilla* spp.) have great potential as a multifunctional aquatic resource that bridges nutritional, medicinal, cultural, and economic domains. Their unique life history strategies, ecological plasticity, and biochemical richness position them as valuable sources of high-quality protein, essential micronutrients, and diverse bioactive compounds. Scientific research has increasingly validated the health benefits long associated with eels in traditional food and medicine systems, particularly their contributions to cardiovascular health, immune function, anti-inflammatory responses, and antioxidant defense. At the same time, eel-based products are gaining commercial traction, with applications ranging from functional foods and dietary supplements to cosmeceuticals and therapeutic formulations. Technological innovations such as enzymatic hydrolysis, nanoencapsulation, and sustainable aquaculture systems are enabling the development of high-value, science-backed eel products with improved bioavailability and shelf life. However, challenges persist wild eel populations continue to decline due to overfishing, habitat fragmentation, and environmental contamination, raising conservation and traceability concerns. The variability in nutrient profiles across species, life stages, and environmental contexts further complicates standardization and regulatory approval of eel-derived products. Addressing these issues requires an integrated strategies that combine conservation science, modern aquaculture, rigorous safety monitoring, and ethical product development. Moreover, cultural knowledge related to traditional processing and therapeutic uses should not be overlooked, as it offers valuable insights into preparation methods that enhance nutrient retention and functional efficacy. Moving forward, interdisciplinary collaboration across food science, pharmacology, ecology, and policy will be essential to ensure the sustainable and equitable utilization of *Anguilla* spp. As global interest in natural and marine-derived health products continues to grow, freshwater eels offer a unique opportunity to contribute to public health, biodiversity conservation, and inclusive economic development, provided that innovation proceeds in tandem with sustainability and cultural respect.

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