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RESEARCH ARTICLE

Hyaluronic Acid as a Bio-functional Ingredient in Food Systems: Technological Applications, Mechanisms, and Future Directions

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Abstract

Hyaluronic acid (HA), a naturally occurring glycosaminoglycan known for its exceptional water-binding capacity and biocompatibility, is gaining increasing attention in the food industry as a multifunctional ingredient. Traditionally used in biomedical and cosmetic applications, HA is now being explored for its roles in functional foods, dietary supplements, texturizers, edible coatings, and advanced delivery systems. This review provides a comprehensive overview of HA's biochemical properties, health-related functions, and emerging food-related applications. We examine its utility in enhancing product texture and stability, supporting joint and skin health, enabling nutrient encapsulation, and modulating flavor perception. Additionally, we highlight current limitations, including high production costs, formulation challenges, regulatory variability, and uncertainties regarding oral bioavailability. Prospects for HA include its integration into sports nutrition, personalized dietary interventions, and sustainable food packaging. By addressing current hurdles through biotechnological and formulation advances, hyaluronic acid is poised to play a significant role in the development of next-generation functional and health-oriented food products.

Keywords: Hyaluronic Acid, Food Applications, Functional Foods, Bioactive Ingredients.

1. Introduction

Hyaluronic acid (HA) is a naturally occurring glycosaminoglycan ubiquitous in connective tissues (Figure 1), distinguished by its remarkable capacity to bind water and form viscoelastic solutions (Graciela et al., 2023). Biochemically, HA's high molecular weight and hydrophilic structure enable it to maintain hydration, elasticity, and lubrication in human tissues. It is a key molecule in maintaining skin hydration and cushioning joints, and it contributes to tissue repair and wound healing (Hryshchenko & Starovoitova, 2024). Beyond its well-established biomedical and cosmetic roles, HA has recently gained prominence in the food industry as a functional ingredient, with regulatory approvals in Asia, Europe, and the US permitting its use in foods and beverages (Food Research Lab). Food-grade HA is now incorporated into diverse products, from yogurts and health drinks to confectionery, where it serves dual purposes: (i) as a technological additive that improves product texture, moisture retention, and stability, and (ii) as a bioactive component that enhances nutritional and health value (Focus Chem, 2024; Shahandasht et al., 2024). Notably, HA's exceptional water-binding and viscoelastic properties enable it to act as a natural thickener, emulsifier, and stabilizer in formulations, thereby extending shelf life and enriching the mouthfeel and appearance of foods (Cowman et al., 2015). At the same time, HA-fortified foods and dietary supplements are marketed for potential health benefits, including improved skin hydration, anti-aging effects, reduced wrinkles, and joint support. Furthermore, emerging innovations in food science are exploring HA for novel applications, such as a natural flavor enhancer to reduce salt in low-sodium foods, underscoring HA's versatility in food technology (Hu et al., 2023; Amin et al., 2025).

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Together, these attributes and applications highlight HA's growing role as a multifunctional ingredient at the nexus of food science and human health, making it an exciting focus of current food technology research and development.

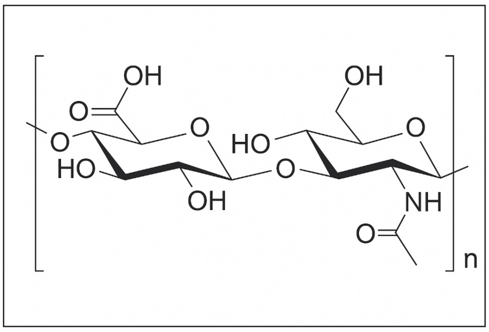

Figure 1. *Chemical Structure of Hyaluronic Acid.*

2. Applications of Hyaluronic Acid in the Food Industry

Hyaluronic acid (HA) has gained increasing attention in the food industry due to its unique functional properties and health benefits. In recent years, regulatory agencies in several countries have approved food-grade HA for use as an additive or supplement, enabling its incorporation into various products (Focus Freda, 2024; Cactus Botanics, 2025a). This section reviews five key application areas of HA in foods, spanning both current practical uses and emerging research-driven developments (Figure 2). These include its role in functional foods and nutraceutical supplements, texture and rheology modification, novel delivery systems for bioactives, edible packaging and coatings, and flavor enhancement or release control.

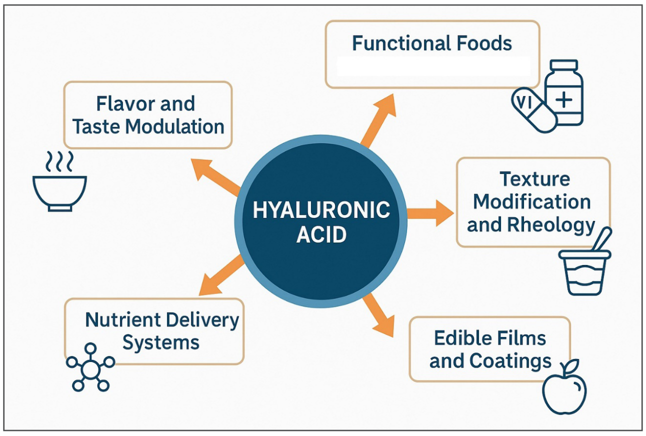

Figure 2. *Schematic representation of functional applications of hyaluronic acid in food systems.*

2.1 Functional Foods and Nutraceutical Supplements

HA is widely used in functional foods and dietary supplements to promote skin, joint, and overall health (Table 1). It has been used as an additive in foods such as yoghurt, milk, and processed meats, as well as in oral supplements (capsules, powders). Its popularity in nutricosmetic products stems from the molecule's known biological roles in tissue hydration and lubrication (Juncan et al., 2021; Graciela et al., 2023). Notably, HA is now promoted as a dietary supplement in countries such as the USA, Canada, and Europe, and is approved as a food ingredient or additive in Japan, Korea, China, and the EU. This broad acceptance underscores its safety and the interest in its potential benefits.

Table 1. *Functional Foods and Nutraceuticals Containing Hyaluronic Acid (Oe et al., 2016; Göllner et al., 2017; Sugiyama et al., 2023; Amin et al., 2025)*

Product Type	HA Formulation	Health Target	Dosage Range	Reported Effects
Yogurt drink	HA + collagen	Joint health, skin	40–200 mg/day	Improved joint mobility, skin hydration
Beauty gummy	Low-MW HA	Skin hydration	60–120 mg/day	Reduced wrinkles, improved skin moisture
Nutritional capsule	Rooster comb extract (HA)	Joint support	80 mg/day	Reduced knee pain in mild osteoarthritis
Protein smoothie	HA + vitamins	Active aging	100 mg/serving	General wellness, hydration support

2.1.1 Health Benefits of oral Hyaluronic Acid

A growing body of evidence supports the efficacy of ingested hyaluronic acid in improving skin and joint parameters. Clinical studies have shown that daily oral intake of HA can increase skin moisture, enhance elasticity, and reduce wrinkle depth after several weeks. In one 12-week placebo-controlled trial, HA supplementation significantly improved skin hydration and reduced wrinkle scores with no adverse effects, highlighting its value as a functional food ingredient for skin health (Hsu et al., 2021). Similarly, HA's well-known role in joint lubrication has led to its inclusion in joint-health supplements and fortified foods. For example, an HA-rich extract from rooster comb added to yogurt was reported to alleviate mild joint discomfort in healthy individuals (Solà et al., 2015). These health outcomes illustrate why HA-fortified foods and beverages are marketed for beauty-from-within and joint-care purposes.

2.1.2 Products and Formulations

Many functional products now leverage HA's benefits. Consumers can find HA added to dairy drinks, smoothies, and nutrition bars, often in combination with collagen or vitamins, to target skin hydration or mobility (Gao et al., 2023; Žmitek et al., 2024). Importantly, studies indicate that adding HA to common foods does not necessarily alter their basic qualities. For instance, supplementing fermented dairy (kefir) with HA has no negative impact on its taste or texture, while potentially providing added benefits for skin or muscle health (Chon et al., 2020). HA's integration into functional foods and nutraceuticals represents a convergence of food technology and wellness trends, positioning this biopolymer as a valuable ingredient for health-promoting diets.

2.2 Texture Modification and Rheology Enhancement

One practical application of HA in foods is as a natural hydrocolloid to modify texture, viscosity, and water retention (Table 2). Chemically, HA is a highly hydrophilic polysaccharide that can bind large amounts of water via its glucuronic acid residues, forming viscous, gel-like solutions. Even at low concentrations, it increases the viscosity of aqueous systems (Dicker et al., 2013). Unlike protein-based thickeners (e.g., gelatin or collagen), HA does not require heat to gel and remains stable over a wide temperature range. However, it typically imparts viscosity rather than a firm gel structure on its own.

Table 2. *Use of Hyaluronic Acid in Texture Modification and Rheology (Sutariya & Salunke, 2023; Li et al., 2025b).*

Food Matrix	HA Type	Inclusion Level	Functional Impact	Applications
Skim milk	High-MW HA	0.2–0.5% w/v	Increased viscosity, creamier mouthfeel	Compatibility depends on protein levels
Yogurt	Medium-MW HA	0.3%	Improved water-holding, texture	No flavor interference
Emulsified sausage	Low-MW HA	0.5–1%	Enhanced juiciness, water retention	High concentrations may destabilize gels
Casein gel	HA + κ-carrageenan	HA: 0.2%, κ: 0.3%	Synergistic viscosity and emulsion stability	Used in 3D food printing

2.2.1 Dairy and Beverage Applications

Dairy products have been a significant focus for HA's texturizing applications. Adding HA to milk and yogurt has been shown to enhance viscosity and improve the products' water-holding capacity (Joshi et al., 2024). For example, incorporating a small percentage (~0.2–0.3%) of high-molecular-weight HA into skim milk significantly increased the milk's apparent viscosity, yielding a richer mouthfeel. However, studies also note that very high-molecular-weight HA can interact with milk proteins, sometimes reducing heat stability or interfering with normal gelation in dairy processes. This indicates that HA's effect on texture depends on its molecular size and concentration. Combining HA with other hydrocolloids can be especially effective, with one report analyzing HA used alongside kappa-carrageenan in milk and found improvements in water retention, foam stability, and emulsion stability at optimized HA-to-carrageenan ratios (Sutariya & Salunke, 2023). Importantly, moderate levels of HA fortification do not seem to detract from dairy product quality. In a kefir study, HA addition did not alter the fermented product's taste or basic properties. Thus, HA can serve as a complementary texture modifier in dairy and beverage formulations, augmenting viscosity and moisture content similarly to plant gums but with the added appeal of its health profile.

2.2.2 Meat and Other Food Textures

HA has also been explored in meat products and other processed foods to improve texture and juiciness. Its strong water-binding capacity can help retain moisture in emulsified meats and gels. In a study on emulsified sausages, adding a food-grade HA (approx. 0.5–1% in the formulation) improved rheological properties and increased water-binding, resulting in a softer, juicier product after cooking (Joshi et al., 2024). The enhanced water retention likely reduces cook-out and dryness in the final sausage. Such findings suggest that HA could function similarly to standard binders, such as phosphates or carrageenan, in processed meats and milk, albeit with a clean-label-friendly image (Sutariya & Salunke, 2023). Beyond these, HA's textural role extends to novel applications such as 3D-printed foods. Researchers have formulated casein–HA composite gels for use as edible inks in 3D food printing, leveraging HA to tune gel consistency (Wang et al., 2023a). While still an emerging area, it exemplifies HA's versatility in modifying rheology. In summary, HA offers food technologists a tool for enhancing texture, increasing viscosity, improving mouthfeel, and retaining moisture across a range of products. Its function is comparable to that of other polysaccharide thickeners, though optimal use may require balancing factors such as molecular weight and interactions with other ingredients.

2.3 Novel Delivery Systems in Bioactive Ingredients

Beyond direct inclusion in foods, hyaluronic acid is gaining interest as a component of delivery systems for encapsulating and releasing nutrients, flavors, and other bioactive compounds (Serini et al., 2023). With its biocompatibility and gel-forming ability, HA serves as an excellent building block for nanocarriers, hydrogels, and other structured delivery vehicles. A recent review noted that numerous HA-based nano-delivery systems have been developed to improve the solubility, stability, and bioavailability of food bioactives such as polyphenols, lipids, and vitamins (Tan et al., 2023). In these systems, HA can play multiple roles, including forming the matrix of hydrogel nanoparticles, acting as a surface coating that provides stability, and serving as a mucoadhesive polymer to prolong the residence time of nutrients in the gastrointestinal tract (Matalqah et al., 2024).

One prominent approach is HA-coated nanocarriers. For example, liposomes, tiny lipid-based capsules for nutrients, can be coated with HA to enhance their performance (Myat et al., 2025). The HA forms a hydrated shell around the liposome, improving its stability against aggregation and protecting its contents during storage and digestion. In a recent study, nanoliposomes loaded with a hydrophobic antioxidant (fisetin) were coated with low–molecular–weight HA (Sun et al., 2024). The HA coating not only maintained the liposomes' spherical integrity but also significantly improved their thermal stability and resistance to digestion. As a result, the bioaccessibility of fisetin increased markedly with the HA-coated liposomes compared to uncoated ones. Such findings illustrate how HA-based encapsulation can control nutrient release and enhance nutrient uptake, enabling functional ingredients to be delivered more effectively in the body. Other studies have explored HA nanogels and nanoemulsions for the delivery of vitamins and phytochemicals, often reporting enhanced stability and sustained release (Boonpetcharat et al., 2025). The mucoadhesive nature of HA, with its ability to bind to mucosal cell surface receptors, is an added advantage, as it can localize bioactive delivery in the mouth or gut. Overall, the use of HA in delivery systems is a cutting-edge area at the interface of food science and biomedicine, aiming to create novel functional foods that protect sensitive ingredients, such as antioxidants, omega-3s, and probiotics, and release them at the right time and place for maximum benefit (Table 3).

Table 3. *Hyaluronic acid in nutrient delivery systems (Nasr, 2016; Ao et al., 2024; Sun et al., 2024; Boonpetcharat et al., 2025).*

Carrier Type	Encapsulated Bioactive	HA Function	Key Benefit
HA-coated liposome	Fisetin (antioxidant)	Stabilizer, mucoadhesive	Improved thermal and digestive stability
HA nanohydrogel	Curcumin	Gel matrix	Controlled release, higher bioaccessibility
HA nanoemulsion	Omega-3 fatty acids	Emulsifier & coating agent	Protection against oxidation
HA microparticle	Polyphenol mix	Encapsulation shell	Targeted release in the small intestine

2.4 Edible Films, Coatings, and Food Packaging Applications

Hyaluronic acid has become a promising component in edible films and coatings, which are biodegradable packaging options that extend food shelf life (Table 4). In these applications, HA is often combined with other film-forming biopolymers, such as polysaccharides or proteins, to create a composite coating that can be directly applied to food surfaces (Cheng et al., 2023). The appeal of HA in these films lies in its moisture retention and bioactivity. Its inclusion can provide antioxidant benefits and help maintain humidity at the food surface, thereby slowing down oxidation and dehydration of the product. Recent studies have demonstrated the effectiveness of HA-based edible coatings on fruits. Al-Temimi et al. (2025) developed a composite coating of HA, pectin, and chitosan to preserve the freshness of apricots. The HA–pectin–chitosan coating significantly reduced weight loss and maintained higher levels of acids and antioxidants in the apricots over 21 days of storage compared to uncoated fruits. By adjusting the ratio of HA to pectin, the researchers optimized the performance of the coating, finding that slightly higher HA content led to the best preservation results. In earlier work, a simple HA-based edible coating was applied to strawberries, resulting in a noticeable extension of shelf-life and retention of the fruits' firmness and nutritional quality (Al-Hilifi et al., 2024). These examples highlight HA's role in active packaging as it not only forms a physical barrier to moisture and gases, like many edible films do, but also contributes chemically by scavenging free radicals and stabilizing the food's own antioxidants.

It is important to note that HA-based edible packaging is still in development. The integration of HA with other coating materials is in its early stages, and ongoing research aims to explore its collaboration with traditional edible film components. Nonetheless, HA's biocompatibility, edibility, and functionality make it a strong candidate for future sustainable packaging solutions. Compared to conventional plastic coatings, HA-based films are biodegradable and are often recognized as generally safe (Kweon & Han, 2023). And compared with other natural coating polymers (such as alginate, starch, or gelatin), HA can provide superior moisture retention and potential health benefits (e.g., a coating that is safe to eat and may even deliver HA's joint and skin benefits to the consumer).

HA can also reduce bacterial contamination in surgical wounds, particularly in guided tissue regeneration procedures. Pirnazar et al. (1999) found that high-molecular-weight HA (1,300 kDa) at approximately 1.0 mg/mL produced the most significant overall growth inhibition across six bacterial strains tested, including *Staphylococcus aureus*, *Actinobacillus actinomycetemcomitans*, *Propionibacterium acnes,* and *Prevotella oris*. The use of HA in packaging not only helps preserve food quality but also aligns with clean-label and eco-friendly trends in the food industry.

Table 4. *Applications of Hyaluronic Acid in edible films and coatings (Kweon & Han, 2023; Trusek et al., 2023; Al-Hilifi et al., 2024; Al-Temimi et al., 2025; Joshi et al., 2025).*

Food Product	Coating Composition	Role of HA	Preservation Outcome
Apricots	HA + pectin + chitosan	Moisture retention, barrier	Delayed ripening, less weight loss
Strawberries	HA film	Antioxidant, hydrating	Maintained firmness and color
Cheese	HA + alginate + EO	Carrier for antimicrobials	Reduced mold growth
Bread	HA + starch film	Moisture retention	Extended shelf life, less staling

2.5 Flavor Enhancement and Release Control

An intriguing novel application of hyaluronic acid in foods is its use in flavor enhancement and controlled flavor release (Table 5). HA itself is essentially tasteless and odorless, but it can influence the perception of other flavors. Recent research has shown that HA can function as a natural flavor enhancer, particularly for salty taste. Due to its high viscosity and mucoadhesive properties, dissolved HA can affect how flavor molecules interact with our taste receptors. For example, one study found that adding a small amount of food-grade HA (0.2–0.4% w/v) to a low-sodium formulation reduced salt content by about 10% without sacrificing the perceived saltiness of the food (Hu et al., 2023). When incorporated into model dishes, such as seasoned fish or steak, HA enabled sodium reduction while maintaining consumer-rated saltiness and overall palatability. This salt-enhancing effect is achieved because HA molecules can bind to sodium ions and the oral mucosa, essentially holding the salt in the vicinity of taste buds for a longer duration. In the cited study, lower-molecular-weight HA was particularly effective, as it promoted greater adhesion and Na^+ ion penetration into a tongue-mimicking sensor, resulting in a more pungent, more sustained salty taste (Snetkov et al., 2020). These findings suggest that HA could be used as a tool for salt-reduction strategies in the food industry, offering healthier formulations without compromising flavor.

Beyond saltiness, HA's mucoadhesive and viscosity traits suggest it may modulate other flavor experiences. HA in a food matrix could slow the release of volatile aroma compounds, potentially prolonging flavor release in products such as chewing gum or lozenges. Its use as a flavor modifier has also been noted in industry reports, with HA being described as a natural flavor enhancer and taste improver (Cook et al., 2018). Comparatively, while substances like collagen or gelatin mainly affect texture and have minimal direct impact on taste, HA's interaction with taste substances at a molecular level offers a unique avenue to influence flavor perception (Fábián et al., 2015). This area is still emerging, but the evidence so far points to hyaluronic acid as a multifaceted additive, not only contributing to texture and healthfulness, but also to the sensory quality of food by controlling and enhancing flavor release in innovative ways.

Table 5. *Hyaluronic Acid as a flavor enhancer and taste modulator (Schlesinger & Powell, 2013; Hu et al., 2023; Huang et al., 2023; Hryshchenko & Starovoitova, 2024).*

Food Model	HA Type	Inclusion Level	Target Flavor Effect	Potential Observed Results
Grilled fish	Low-MW HA	0.3% w/v	Enhance saltiness	10% NaCl reduction, no taste loss
Steamed steak	Low-MW HA	0.4% w/v	Sodium reduction support	Maintained perceived salt intensity
Chewing gum	High-MW HA	0.2% w/w	Prolonged mint flavor release	Extended sensory perception by 30%
Soup seasoning	HA + glutamate	0.25% HA	Umami retention	More pungent aftertaste, better mouthfeel

2.6 Role of Hyaluronic Acid in Sports Nutrition and Active Lifestyle Products

The integration of hyaluronic acid (HA) into sports nutrition and active lifestyle products is an emerging area within the functional food sector, driven by increasing consumer demand for ingredients that support joint mobility, recovery, and overall musculoskeletal health (Yang, 2025). HA's biological functions in connective tissue lubrication, cartilage maintenance, and anti-inflammatory activity position it as a promising component for athletic and physically active populations. These benefits are particularly relevant for mitigating exercise-induced joint discomfort and promoting recovery, as repetitive mechanical stress on joints and soft tissues can cause microtrauma and inflammation (Table 6).

HA has been incorporated into various sports-focused formulations, including protein powders, ready-to-drink recovery beverages, energy bars, and soft chews (Cactus Botanics, 2025b). These products often pair HA with complementary ingredients, like collagen peptides, glucosamine, chondroitin sulfate, or branched-chain amino acids (BCAAs), to offer synergistic benefits for joint integrity and performance recovery. In a randomized clinical trial, subjects who consumed a beverage containing HA and hydrolyzed collagen experienced a significant reduction in knee pain and improved range of motion after weeks of resistance training, compared with a placebo group. These findings align with other evidence suggesting that orally administered HA may reduce joint friction and modulate inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), which are elevated post-exercise (Marinho et al., 2021; Lippi et al., 2023).

In addition to joint support, HA is being explored for its hydration-enhancing properties. Because HA can bind up to 1,000 times its weight in water, it is hypothesized to aid in cellular hydration and fluid retention, factors critical for athletic endurance and thermoregulation (Khunmanee et al., 2017). Although direct evidence in athletic settings remains limited, several sports drinks and electrolyte powders now market low-molecular-weight HA as a hydration-support ingredient, especially for long-duration events or high-heat conditions.

From a product development standpoint, HA's inclusion in sports nutrition presents both opportunities and formulation challenges. Its solubility and viscosity must be carefully balanced to ensure palatability and ease of use, especially in beverages or powders intended for rapid consumption. Flavor neutrality and stability across a wide pH range are also critical, particularly in acidic sports drinks or fruit-flavored gels (Kumar et al., 2022). Novel encapsulation techniques, such as spray drying HA into microbeads or integrating it into hydrogel matrices, are being investigated to enhance stability and bioavailability in athletic products (Minelgaitė et al., 2025).

As awareness of joint health and recovery continues to rise among amateur and professional athletes, HA is poised to become a functional ingredient of interest in performance-driven foods and supplements. Its growing visibility in the active lifestyle segment reflects broader consumer trends favoring preventive wellness and recovery-focused nutrition. With continued research and innovation, HA may establish a lasting role in sports nutrition as both a performance aid and a protector of long-term joint health.

Table 6. *Hyaluronic Acid in sports nutrition and active lifestyle foods (Salem et al., 2024; Krzyżanowska et al., 2025)*

Product Type	HA Dosage	Co-ingredients	Health Focus	Study Outcome
Protein shake	100 mg	Collagen, Vitamin C	Joint mobility	Reduced stiffness after 8 weeks
Electrolyte beverage	50–80 mg	Electrolytes, HA	Hydration enhancement	Improved fluid retention in athletes
Energy bar	80 mg	BCAA, HA	Recovery, joint health	Decreased post-exercise discomfort
Gummy supplement	120 mg	HA + coenzyme Q10	Skin + joint recovery	Increased mobility and hydration scores

3. Challenges and Potential Applications in the Future of Hyaluronic Acid in the Food Industry

3.1 Challenges in the Development and use of Hyaluronic Acid in Foods

Despite the promising applications of hyaluronic acid (HA) in the food industry, several scientific, technological, and regulatory challenges must be addressed to facilitate its broader integration into food systems. One of the foremost limitations is the cost and scalability of production. Food-grade HA is typically produced via microbial fermentation using *Streptococcus zooepidemicus*, *Bacillus subtilis*, or genetically engineered *Lactococcus lactis* (Serra et al., 2023). However, the yields can be inconsistent, and the downstream purification processes are energy-intensive and expensive, particularly for high-molecular-weight HA, which is often preferred for its water-binding and rheological properties. The substrate cost, fermentation optimization, and quality control at an industrial scale pose significant barriers to widespread use, especially in low-cost, mass-market food products. Research into alternative fermentation systems, including the use of agricultural waste or dairy byproducts such as whey as carbon sources, has demonstrated cost reductions and improved sustainability, but commercial uptake remains limited. Moreover, standardization of molecular weight and purity across batches is essential, as these parameters directly influence HA's functional performance and bioactivity. Without precise control, manufacturers may encounter issues with solubility, viscosity, and inconsistency in health benefits, which can ultimately affect consumer trust and regulatory compliance.

Another major challenge lies in formulation compatibility and stability within complex food matrices. HA's high hygroscopicity and strong water affinity make it a desirable humectant and texturizer, but they also complicate its interactions with other ingredients, such as proteins, emulsifiers, and hydrocolloids (Wang et al., 2023b). In dairy systems, for example, HA may interfere with casein micelle aggregation during fermentation or heating, leading to undesirable textural outcomes (Siefen et al., 2022). Similarly, in meat emulsions or plant-based gels, improper HA concentrations or molecular configurations may weaken the network structure rather than reinforce it, primarily if water migration or phase separation occurs during storage. These effects can be compounded by environmental stressors such as temperature, pH, and ionic strength, which can trigger HA depolymerization, altering its molecular weight and efficacy. In acidic environments, such as those found in fruit-based beverages or flavored yogurts, HA's stability decreases, leading to reduced viscosity and bioactivity (Fallacara et al., 2018). Consequently, product developers must carefully consider the food matrix, processing conditions, and HA specifications (e.g., molecular weight, concentration, degree of modification) to ensure compatibility and efficacy. Encapsulation technologies, such as lipid- or polysaccharide-based carriers, may offer a partial solution by stabilizing HA during processing and gastrointestinal transit, though these add further complexity and cost (Sun et al., 2025).

From a regulatory perspective, the landscape for hyaluronic acid in food is evolving but remains fragmented across different jurisdictions. In the European Union, HA is approved as a Novel Food and may be added to supplements and to specific food categories, such as dairy products, beverages, and confectionery. The European Food Safety Authority (EFSA) generally recognizes HA as safe at consumption levels of 200 mg/day or less. Long-term efficacy studies are limited, and functional claims, particularly related to skin hydration or joint health, require rigorous scientific substantiation. In the United States, HA has been granted GRAS (Generally Recognized as Safe) status for specific food applications (Sze et al., 2016). Still, FDA scrutiny has increased regarding its biological effects, particularly whether ingested HA exerts pharmacological activity akin to supplements or medical interventions. In China, HA has recently been allowed in general foods, yet with mandatory warning labels and restrictions for vulnerable groups such as infants and pregnant women, reflecting a precautionary approach. Regulatory authorities across regions have raised concerns about the lack of harmonized standards for HA identity, purity, and molecular weight, which complicates both safety assessments and labeling requirements. Moreover, since most commercial HA is derived from microbial fermentation, strain safety and potential allergenicity must be carefully evaluated, particularly when using genetically modified organisms. These regulatory ambiguities pose significant barriers for global food companies seeking to commercialize HA-enriched products consistently across markets.

Additionally, there are scientific uncertainties regarding the bioavailability and mechanism of action of orally ingested HA. While some clinical trials have shown improvements in skin hydration, joint function, and anti-inflammatory markers, the mechanisms underlying these effects remain poorly understood. Evidence suggests that HA may be broken down by intestinal microbiota into oligosaccharides that are subsequently absorbed and exert systemic effects, or that high-molecular-weight HA may interact directly with gut-associated lymphoid tissues (Zhao et al., 2023). However, these hypotheses lack definitive confirmation, and individual variability in gut microbiota may influence HA degradation and efficacy. These unknowns challenge efforts to establish clear structure-function relationships, dose-response guidelines, and long-term safety profiles, critical for securing health claims and consumer confidence. Finally, consumer perception and education represent softer but no less significant challenges. Many consumers associate HA with injectable beauty treatments or topical skincare and may be skeptical of its role as a functional food ingredient. Communicating the benefits, safety, and value of HA-enriched products in a transparent, scientifically grounded manner will be essential to market success. In summary, the current limitations in cost-effective production, formulation stability, regulatory clarity, bioavailability research, and consumer acceptance represent critical hurdles that must be addressed through coordinated interdisciplinary efforts.

3.1 Prospects and Innovative Applications

The future of hyaluronic acid in the food industry is promising, with emerging technologies and innovative applications offering exciting pathways for expansion. One of the most impactful directions is the development of targeted delivery systems using HA-based nanocarriers. Given HA's natural biocompatibility and affinity for specific receptors (e.g., CD44), it is an ideal candidate for the construction of smart delivery vehicles that can transport sensitive nutrients, antioxidants, or probiotics through the digestive system and release them at specific sites. Researchers are increasingly leveraging HA's physicochemical properties to formulate hydrogels, liposomes, and nanoemulsions that enhance the bioavailability of poorly soluble compounds such as curcumin, polyphenols, and omega-3 fatty acids. For instance, HA-coated liposomes have been shown to significantly improve the stability and gastrointestinal uptake of fisetin, a plant-derived antioxidant with neuroprotective potential. By extending this technology to functional foods and beverages, manufacturers can design next-generation products that deliver targeted, sustained nutrients, thereby increasing efficacy and consumer appeal (Koppula et al., 2025).

Another fertile area for innovation is in edible films and active packaging materials, where HA's moisture-retentive and antioxidative properties can be harnessed to enhance food preservation. When combined with other biopolymers such as chitosan, pectin, or alginate, HA can form transparent, flexible coatings that reduce oxidation, microbial growth, and moisture loss on fresh produce, bakery items, or meats (Anirudhan et al., 2022). Recent studies have demonstrated that HA-based composite coatings can significantly prolong the shelf life of apricots, strawberries, and cheese, without altering their taste or texture (Al-Hilifi et al., 2024). These coatings not only serve as physical barriers but may also incorporate bioactive compounds, such as essential oils or natural antimicrobials, that are gradually released, creating a multifunctional preservation system. Moreover, because HA is biodegradable and generally recognized as safe, these edible films align with the growing demand for sustainable, clean-label packaging solutions. With ongoing advances in food-grade polymer chemistry, HA-based materials may soon be tailored for specific product categories, moisture levels, and shelf-life goals.

In addition to its functional and preservative roles, HA offers unique opportunities in flavor enhancement and sensory modulation. Its mucoadhesive properties allow it to retain flavor molecules near the taste receptors for extended periods, potentially enhancing the perception of saltiness or sweetness without increasing sodium or sugar content. In one recent study, HA was found to increase perceived saltiness in low-sodium formulations by holding sodium ions closer to the tongue surface, thereby enabling sodium reduction without compromising taste (Hu et al., 2023). This flavor-locking ability opens the door to healthier formulations of processed foods and snacks, addressing public health goals while maintaining palatability. Moreover, HA's thickening ability can improve mouthfeel and creaminess in reduced-fat or plant-based products, offering an appealing texture profile without artificial stabilizers (Liao et al., 2021). These attributes make HA an asset in the development of next-generation sensory experiences, particularly for reformulated or clean-label foods.

Furthermore, HA's intrinsic health-promoting properties present exciting opportunities for next-generation functional foods and nutricosmetics. As consumer interest in beauty-from-within and personalized nutrition grows, HA-fortified products, such as beverages, dairy alternatives, and gummies, are poised for growth. Combining HA with synergistic compounds like collagen peptides, vitamin C, or coenzyme Q10 could yield multifunctional products that support skin health, joint mobility, and immune modulation (Li et al., 2025a). Advances in multi-omics technologies may also enable personalized HA supplementation, in which formulations are tailored to an individual's microbiome, age, or genetic markers to optimize efficacy. These future products could be marketed not only as wellness boosters but also as adjuncts to medical nutrition therapies for osteoarthritis, dry eye syndrome, or gastrointestinal conditions, expanding HA's scope from general wellness to targeted dietary interventions.

Finally, innovations in synthetic biology and green biomanufacturing are likely to transform HA production, making it more sustainable, scalable, and customizable. Researchers are engineering microbial strains with improved fermentation efficiency, resistance to phage contamination, and the ability to produce HA of specific molecular weights with minimal downstream processing. Coupled with renewable feedstocks such as agro-industrial residues, these advances could dramatically reduce production costs and environmental impact. Soon, it is conceivable that modular biorefineries will produce HA tailored for distinct food applications, whether as a high-viscosity thickener, a low-MW bioactive, or a film-forming agent, each with unique structural and functional characteristics. As regulatory frameworks mature and scientific understanding deepens, the food industry will likely see an expansion of HA's functional definition, not just as an additive but as a biologically meaningful component of food design.

To sum up, while current barriers to the widespread adoption of hyaluronic acid in the food industry remain significant, they are far from insurmountable (Iaconisi et al., 2023). Ongoing advancements in biotechnology, material science, and sensory research are steadily expanding the feasible uses of HA in functional food systems (Figure 3). Through strategic investment in research and development, industry collaboration, and consumer education, HA can evolve from a niche ingredient to a cornerstone of next-generation food innovation, contributing not only to product quality and shelf stability but also to public health, environmental sustainability, and the personalization of nutrition.

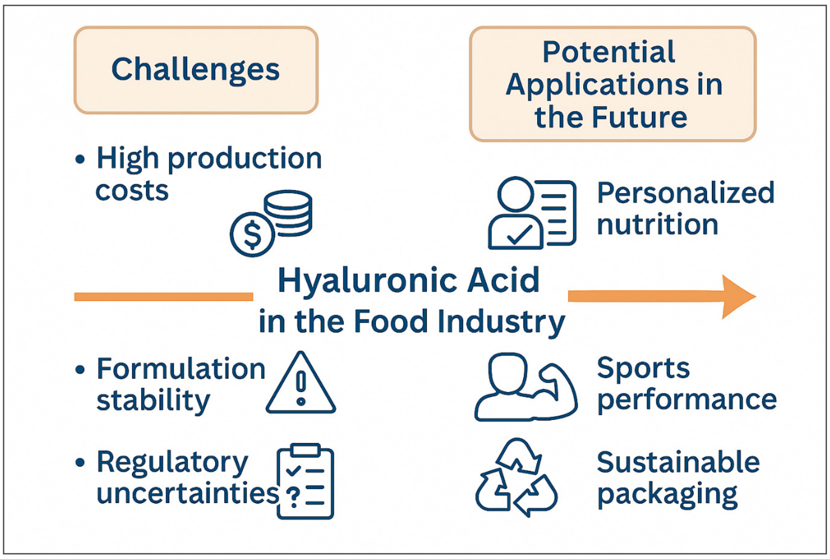

Figure 3. *Key barriers and emerging opportunities for hyaluronic acid applications in food systems.*

4. Conclusion

Hyaluronic acid has rapidly transitioned from a biomedical and cosmetic compound to a multifunctional ingredient with growing relevance in the food industry. Its unique physicochemical properties, particularly its high water-binding capacity, biocompatibility, and viscoelasticity, enable a broad spectrum of food-related applications, including functional foods and dietary supplements, texture enhancement, bioactive delivery systems, edible packaging, and even flavor modulation. The increasing inclusion of HA in food products aligns with broader consumer demands for health-promoting, natural, and scientifically backed ingredients. Despite its promising functionality, integrating HA into mainstream food systems poses challenges. High production costs, formulation stability, regulatory inconsistencies, and limited clinical evidence on oral efficacy present obstacles that must be addressed through multidisciplinary innovation. Nevertheless, ongoing advances in fermentation technology, encapsulation systems, and sustainable sourcing are paving the way for more cost-effective and targeted uses. As research continues to clarify HA's mechanisms of action and optimal delivery formats, its role in personalized nutrition, sports performance, and food sustainability is expected to expand. With strategic development and regulatory alignment, hyaluronic acid holds significant potential to become a key component in the next generation of functional and health-enhancing food products.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

5. References

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