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Exploration of the Differentiated Applications of Gelatin in the Food and Biomedical Fields

Siying Lu

Shanghai Kaiwen and Ealing International School, Shanghai, China
15002197715@163.com

Abstract. Gelatin is a macromolecular hydrophilic colloid formed by collagen hydrolysis. Owing to its low cost, easy availability, biocompatibility, and biodegradability, it is widely used in the food and biomedical fields. This paper explores the latest progress in gelatin applications in food technology and biomedicine through a literature review and attempts to elaborate on how these applications differ between the medical and food fields. The study finds that the application of gelatin in the food field focuses on functional development, such as improving texture, encapsulation of bioactive compounds, and fat replacement, and is gradually shifting towards a non-raw-material trend, where gelatin serves more as a functional additive rather than a primary ingredient. In the medical field, its applications are mainly realized through nanotechnology, high-strength hydrogels, and other means in drug-delivery and wound-repair materials, leveraging its excellent biocompatibility and cell adhesion properties. Furthermore, emerging areas such as 3D bioprinting and tissue engineering scaffolds are gaining attention. Promoting the standardization, large-scale production, and sustainable innovation of the gelatin industry is of great significance for advancing cross-field application research and boosting sustainable development.

Keywords: Gelatin, Drug Delivery, Biocompatibility, Food Processing, Differentiated Applications

1. Introduction

Gelatin is a natural polymer obtained by the hydrolysis and degradation of collagen. It has the advantages of a cell-adhesion structure, biocompatibility, biodegradability, low immunogenicity, and non-toxicity. Currently, its raw materials are mainly derived from low-cost animal by-products, such as cattle, pigs, and fish, making gelatin an indispensable material in both the medical and food fields. At present, gelatin has been widely used in biomedicine, food processing, and other fields. However, the differentiated performance requirements of the two fields lead to significant differences in their application paths, and existing research remains insufficient in systematically sorting out and comparing their application development. Based on this, this paper systematically reviews the relevant literature in recent years, sorts out the latest application progress of gelatin in the food and biomedical fields, focuses on elaborating its differentiated application characteristics and core driving factors, and provides a theoretical reference for targeted optimization of gelatin modification technology and expansion of cross-field application value.

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2. Formation mechanism and core properties of gelatin

2.1. Raw materials and preparation of gelatin

Gelatin preparation is centered on collagen hydrolysis, and its source distribution and raw material pretreatment directly affect product performance. Collagen mainly exists in animal bones, tendons, muscle sheaths, ligaments, muscle fascia, cartilage and skin, and is the most abundant and widely distributed protein in mammalian bodies. Raw materials need to undergo pretreatment processes, such as degreasing, decalcification, and cleaning, to remove impurities and prevent adverse effects on the purity and functional properties of gelatin.

Collagen molecules have a unique triple-helical superstructure, which is very stable and cannot be disrupted by typical heating temperatures or short-term heating. This robust tertiary structure is destroyed by hydrolysis, and soluble polypeptide chains that form gelatin, while the amino acid composition of collagen is retained [1]. Existing studies have adopted a variety of methods for gelatin preparation. Wang et al. systematically compared the extraction effects of the acid method, acid-alkali method, and acid-enzyme method using chicken heads as raw mterial. The results showed that the acid-alkali method had the highest yield (10.08%), which was significantly higher than those of the acid-enzyme method (9.08%) and the acid method (2.52%). Further analysis of product characteristics showed that the gelatin prepared by the acid-alkali method exhibited typical Type A gelatin characteristics, including a high protein content (73.33%), low ash content (0.90%), moderate solubility (66.81%), and wide pH adaptability, thus achieving the best comprehensive performance [2].

At present, according to the differences in hydrolysis medium and catalytic mode, the mainstream preparation processes can be divided into four categories: alkaline method, acid method, composite process and enzymatic method, with the alkaline method being the most commonly used (see Table 1) [3].

Table 1. Four typical preparation processes [3]

Process Type	Mechanism	Advantages	Limitations
Alkaline method	Alkaline solution breaks collagen cross-links and promotes peptide chain dissociation	High gel strength and good product stability	Long production cycle and high waste liquid pollution
Acid method	Collagen swells and is hydrolyzed under acidic conditions	Simple process and short cycle	Low yield and relatively weak gel strength
Enzymatic method	Protease specifically cleaves the non-helical region of collagen	Mild conditions and good retention of biological activity	High enzyme cost and complex process control
Composite process (acid-alkali/acid-enzyme method)	Acid/alkali pretreatment combined with enzymatic hydrolysis or hydrothermal extraction	Balances yield and quality, and can regulate product characteristics	Increased difficulty in optimizing process parameters

2.2. Core properties of gelatin

Gelatin contains 18 kinds of amino acids, 7 of which are essential for the human body. Excluding less than 16% water and inorganic salts, the protein content of gelatin exceeds 82%, making it a

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high-quality protein source. In terms of functional characteristics, gelatin exhibits diverse advantages.

First, gelatin has good gel properties. A gelatin aqueous solution forms a gel at 30–40°C, and the gel strength is significantly higher at 0–10°C, a process that is thermoreversible [4]. Gel strength is significantly affected by molecular weight distribution, the content of imino acids (proline and hydroxyproline), and extraction processes.

Second, derived from natural collagen hydrolysis, the amino acid sequence of gelatin retains cell-recognition sites (such as the RGD sequence), which can promote cell adhesion, proliferation, and differentiation, endowing gelatin with excellent biocompatibility [5]. Gelatin can be gradually degraded in the body through enzymatic hydrolysis and is a natural source of amino acids with no risk of immunogenic residues [6].

In addition, the gelatin molecular chain is rich in active groups, such as amino and carboxyl groups, which enable it to undergo conformational changes in response to external stimuli, such as temperature, pH, and ionic strength, thereby regulating functional behaviours, such as drug release rate [7]. By regulating the degree of hydrolysis, various forms of gelatin can be obtained, from low-viscosity fluid gelatin to high-elastic hydrogels, thus adapting to diverse process requirements such as injection, freeze-drying and 3D printing [1, 7].

3. Applications and practice of gelatin

3.1. Applications of gelatin in the medical field

3.1.1. Drug delivery systems

Gelatin has a long history of being used as a capsule shell material. With high tissue compatibility with the human body due to its amino acid composition, gelatin can have its film-forming properties regulated through acid or alkaline processes to encapsulate water-soluble or fat-soluble drugs, forming dosage forms such as hard and soft capsules. It can not only mask the unpleasant smell of drugs and protect active ingredients from environmental factors, but also rapidly dissolve in the gastrointestinal tract to achieve precise drug release and efficient absorption [2].

In the field of nano-delivery, gelatin-based carriers show significant advantages. Wu et al. prepared gelatin nanoparticles by a two-step desolvation method, which exhibited excellent anti-protein adsorption properties. Studies have shown that they effectively prolong the blood circulation time and improve drug delivery efficiency [5]. Ye et al. constructed gelatin microcapsules connected via borate ester bonds using the complex coacervation method, achieving the selective release of celastrol in the matrix metalloproteinase (MMP) microenvironment. This system effectively reduces toxicity to normal cells while retaining anti-tumour activity [8].

3.1.2. Wound repair materials

Gelatin-based biomaterials can promote wound hemostasis, enhance the antibacterial and anti-inflammatory effects around wounds, and drive the regeneration of blood vessels and epithelial cells; gelatin sponges also show excellent performance in wound repair [6]. Gelatin can be combined with other materials (such as sorbitol) to prepare medical hemostatic sponges, hydrogel dressings and other products. Their porous structure can quickly absorb wound exudate and blood, activate platelets, and promote the formation of blood clots, while at the same time providing a natural matrix for vascular regeneration and epithelial cell proliferation, exerting multiple effects,

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including hemostasis, antibacterial, anti-inflammatory, and tissue repair [9]. Studies have shown that combining fluid gelatin with gelatin sponge can significantly improve hemostatic efficiency and fusion quality in spinal decompression and fusion surgery.

3.2. Applications of gelatin in the food field

3.2.1. Traditional food processing

Owing to its favorable gelling properties, gelatin serves as a key raw material in jelly, pudding, marshmallows, and other similar products. In meat products such as sausages and ham sausages, typically added at 1%-3%, gelatin reduces cooking loss, enhances water and fat retention, and improves the taste and texture of the final product.

3.2.2. Functional food development

Gelatin is a high-protein raw material with no fat and cholesterol, low calorie and rich in beneficial amino acids such as glycine and proline, which conforms to the concept of modern healthy diet. Wang et al. pointed out that through molecular structure design, gelatin can be developed into a functional food base material with specific functions, such as controlled-release nutrient carriers and intestinal flora regulators.

3.2.3. Food preservation and packaging

In recent years, gelatin has been widely used as a preservation material due to its good film-forming properties and biodegradability. As a binder and water retainer, gelatin is added to products such as ham, sausages, and fish balls, where it can enhance the bonding force between muscle tissues, reduce water loss during processing, improve product elasticity and slicing performance, and extend shelf life [8].

3.3. Comparison of application differences

The differences in gelatin applications between the food and medical fields are shown in Table 2. As a bridge material connecting natural collagen and high-end applications, the differentiated application of gelatin in the food and biomedical fields represents a typical example of "the same molecular skeleton, diverse functional expressions." The food field pursues a balance between sensory experience and cost-effectiveness, while the biomedical field focuses on the unification of biological safety and functional precision. The demand differences between the two have driven the dual-track development of gelatin modification technology.

Table 2. Differences in gelatin applications between the food and medical fields

	Food Field	Medical Field
Functional Requirements	Coagulation, thickening, taste enrichment; water retention and bonding for fresh-keeping	Hemostasis, anti-inflammation, wound repair
reparation Process	Mainly alkaline/acid methods, simplified process, focusing on deodorization and decolorization	Mainly alkaline/enzymatic methods, multi-step purification, aseptic processing, low endotoxin control
Typical Applications	Jelly, gummy candy, sausage/ham, clarification of alcoholic beverages	Capsule production, hemostatic sponges

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Table 2. (continued)

Key Performance Indicators	Gel strength, transparency, neutral flavor, thermoreversibility	Biocompatibility, controllable degradability, mechanical matching, modification flexibility

4. Challenges and optimization strategies for gelatin applications

4.1. Main challenges faced

Despite its wide application, gelatin still faces many challenges. In the medical field, the use of gelatin in wound treatment is still in its early stages, and there are few large-scale clinical trials to verify its effectiveness. In addition, although the hemostatic effect of synthetic gelatin-based materials has been confirmed, their complex processing methods result in high product prices, primarily because of their widespread use [6]. At the same time, pharmaceutical-grade gelatin requires extremely strict batch production record management, and any missing records may pose quality risks [10]. In the food field, there is also the problem of high processing costs. Moreover, as gelatin is mostly derived from animal tissues, it cannot meet the needs of vegetarians and other groups, whereas alternative raw materials, such as fish skin, face technical bottlenecks, including weak thermal stability and insufficient gel strength [4, 9]. In addition, traditional extraction processes face challenges such as high processing costs and environmental pollution, which hinder the industry's sustainable development.

4.2. Optimization strategies and future directions

In response to the above challenges, future research should further optimise and target the bottlenecks in each field for solutions.

In the medical field, to overcome the limitations of gelatin's weak mechanical properties and its single-function nature, it is necessary to introduce advanced material design concepts. Nanotechnology is used to prepare gelatin particles with a uniform particle size to optimise drug delivery. Multi-centre clinical trials should be conducted for new preparations, such as fluid gelatin [11]. Vigorously develop intelligent delivery systems and high-performance scaffold materials. For example, the anti-protein adsorption properties of gelatin nanoparticles should be utilised to prolong drug circulation time, or microcapsule systems should be developed that release drugs selectively in specific enzymatic microenvironments [5, 8]. In addition, for scenarios such as wound repair and spinal surgery, further verify the long-term safety of gelatin composite materials for hemostasis, anti-inflammation, and tissue induction, and promote standardisation [7].

To address the instability in the supply of animal-derived gelatin, it is necessary to accelerate the industrialisation of non-traditional raw materials, such as fish skin. Combine the optimisation of hydrothermal parameters with online monitoring technology to improve batch stability [2]. Secondly, promote green extraction processes to reduce production costs while ensuring high protein and low ash content. Finally, the application of gelatin in intelligent packaging should be expanded to utilise its film-forming property and biodegradability for loading natural antibacterial agents, thereby extending the shelf life and increasing the added value of food [7].

5. Conclusion

This paper systematically identifies the core differences in raw material selection, process regulation, and functional requirements of gelatin between its applications in the medical and food fields. The food field focuses on the transformation of non-traditional raw materials and green modification technologies, while the medical field focuses on precise drug delivery, wound repair and hemostatic functions, and realises functional upgrading through nanoscale design.

However, this study still has limitations: first, it is mainly based on existing literature and secondary data, lacking data from large-scale, multi-centre randomised controlled clinical trials. Second, the exploration of non-traditional raw materials, such as fish skin, does not fully account for economic and other factors and lacks further research into high-performance alternatives. Future research should combine molecular simulations to elucidate the regulatory mechanisms underlying gelatin conformational changes in interfacial behaviour and cell response, and further collect clinical data to provide evidence for the application of new gelatin preparations in complex surgical scenarios.

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