Applications of Gellan Gum

Subjects: Agriculture, Dairy & Animal Science

Contributor: Raghad Abdl Karim Abdl Aali , Shayma Thyab Gddoa Al-Sahlany , Alaa Kareem Niamah

Gellan gum (GG) is a linear, negatively charged exopolysaccharide that is biodegradable and non-toxic. When metallic ions are present, a hard and transparent gel is produced, which remains stable at a low pH. It exhibits high water solubility, can be easily bio-fabricated, demonstrates excellent film/hydrogel formation, is biodegradable, and shows biocompatibility. These characteristics render GG a suitable option for use in food, biomedical, and cosmetic fields.

gellan *Sphingomonas* hydrogels

1. Introduction

A hydrogel consists of a hydrophilic polymeric network composed of polymers and their solvents. It can absorb significant amounts of solvent and keep it within matrices [1]. Polymers undergo conformational changes in response to variations in solvent conditions like ionic strength and temperature, as described by Tanaka [2]. Hydrogels have extensive applications in the food industry due to their safety features and efficient three-dimensional cross-linked structures, such as fat substitutes, package delivery systems, and edible films [3][4][5]. Carbohydrates and proteins are frequently used as monomers for developing hydrogels. Combining two or more monomers can result in a hydrogel system with enhanced physicochemical properties compared to a single polymer gel [6]. Polysaccharide-based hydrogels have been the focus of significant interest and investigation because of their favorable bioactivity, biocompatibility, and biodegradability. Research has demonstrated that hydrogels composed of polysaccharide-polysaccharide complexes, which exhibit good compatibility, can form a tightly woven interpenetrating network. This can alter the gelation time, improve water retention, and boost the gel's strength [7]. Enhanced features have been documented for konjac glucomannan-gellan gum, erythritol-curdlan, konjac glucomannan-curdlan, and gellan-xyloglucan complexes [8][9][10][11]. Hence, complexes of polysaccharides could enhance gel properties by leveraging synergistic interactions, rendering them a focal point in the development of gel products.

In recent years, microbial polysaccharides have garnered a great deal of interest due to the amazing functions and vast industrial applications they possess and the fact that they can be produced in a sustainable manner across commercial scales. Methods from the fields of system biology and biochemical engineering may be used to further reduce the costs associated with their manufacture [12]. The ingredients that comprise microbial polysaccharides include both carbohydrate and non-carbohydrate components. They are dependent on the genus of the microorganism that produces the microbial polysaccharide to determine the non-carbohydrate ingredient, which may vary from acetate to pyruvate and even succinate in certain cases [13]. When it comes to microbial polysaccharides, sphingans are distinguished by their tetrasaccharide repeating backbone, which is accompanied by a variety of substitutions on the side chain. Depending on factors such as the linkage pattern, the length of the polysaccharide, the intra-molecular connection, and the polymeric cross-linking with molecules in the surrounding area, the individual sphingan is a rheologically distinct entity [14]. There are considerable differences in the chemistry and functional features of the various sphingans, despite the fact that all of the sphingans are generated by different strains of *Sphingomonas* species [12].

Gellan gum (GG) is an exopolysaccharide secreted outside of the bacterial cell, produced by species from the genus *Sphingomonas*, and it is soluble in water. In 1978, bacteria that produce gellan were found and isolated by the former Kelco division of Merck & Inc. Company, Rahway, NJ, USA. The bacteria were discovered in lily tissue from a natural pond in Pennsylvania. Initially recognized as a substitute gelling agent for agar in solid culture media to support the growth of different microorganisms due to its ability to withstand high temperatures up to 120 °C, it was introduced as a commercial product under the trademark Gelrite GG. It found applications in the pharmaceutical, cosmetic, and food industries [15]. The composition of GG includes three fundamental units: α-L-rhamnose, β-D-glucose, and β-D-glucuronate, in a ratio of 1:2:1. GG possesses transparency, high tensile strength, and a pleasant taste. It exhibits high stability to temperatures and resistance to acidic enzymes. With a molecular weight of up to 500 KDa, it forms a viscous solution when dissolved in aqueous solutions but remains insoluble in ethanol. This compound maintains stability across a broad pH range of 2–10. GG finds extensive applications in the food industry as a thickening agent, binding agent, stabilizer, emulsifier, and gelling agent [16].

GG is derived from various species of *Sphingomonas* bacteria, like *S. pseudosanguinis* and *S. yabuuchiae*, utilizing fat residues like glycerol as a nutritional medium for these bacteria [15]. Huang and colleagues [16] demonstrated the potential of utilizing corn waste to produce GG from *S. paucimobilis* bacteria. The production yield achieved a level of 14 g/L in the production medium. Utilizing molasses and cheese whey as the media, fermentation was carried out to produce GG from *S. azotifigens* bacteria, resulting in a gum with a molecular weight of 890 KDa [17]. GG is utilized in various food industries and is frequently utilized in the production of juices, sweets, beverage powders, jelly, jams, marmalades, vegetable butter (margarine), and yogurt [18][19][20]. In 1990, the gum underwent evaluation by the Scientific Committee for Food of the European Union. It received unconditional approval for use in food due to evidence of cytotoxicity. The gum was assigned the symbol E418 and can be used at concentrations of 0.1–1.0% [21].

2. Applications of Gellan Gum

2.1. Food Applications

GG is a food additive that has been utilized for an extended period because of its functional properties. Currently, there is a growing interest in this field because of the advancements in new materials and the enhancement of food systems to improve their rheological properties [22]. GG was utilized in colloidal aqueous solutions due to its capacity to produce gelatinous substances at low concentrations and establish a network in contrast to other polycarbonates employed in foods (**Table 1**). Adjusting the gum, like eliminating the acetyl group, led to the production of gelatinous materials with unique physical characteristics, enabling its utilization in various food product models [23].

Table 1. Typical food applications of gellan gum.

Main Food Field	Representative Food Product	References
Beverages	Beverages with jelly and fruit	[23]
Sugar	Starch, jelly, stuffing, and candy floss	[24]
Jam	Low-heat jam, synthetic jam, and bread stuffing	[25]
Synthetic food	Synthetic fruits, synthetic vegetables, and synthetic meat	[18][19]
Water-based gel	Dessert gel and decorative jelly	[26]
Pie stuffing and pudding	Fast-food dessert, tinned pudding, pre-cooked pudding, and pie stuffing	[27]
Pet food	Tinned meat segment and gel pet food	[28]
Sugar coating and sugar frost	Sugar coatings for cakes and tinned sugar frost	[27]
Milk products	Ice cream, jelly milk, yogurt, and frozen milk	[29]

In various industries, polygons found in foods are combined with other elements to eliminate certain undesirable characteristics. For instance, GG has low mechanical strength, so when combined with pullulan, it resulted in a product with favorable sensory properties and distinctive rheological characteristics [30]. In a study by Kanyuck et al. [31], it was demonstrated that combining GG with maltodextrin resulted in the formation of a robust, intertwined network. This blend was utilized in low-fat items as a substitute for fat while also providing a sensation of satiety. In a study by Sapper et al. [32], it was found that incorporating thyme oil with GG in creating a film for fruit preservation resulted in the development of an edible composite film. This film extended the preservation period by reducing evaporation and inhibiting the growth of microorganisms.

Recently, it was discovered that GG can act as a stabilizing agent and also preserve volatile oils in coated fruits. It can improve the percentage of ascorbic acid and antioxidant activity, enhance preservation processes, and extend the storage life of highly perishable fruits, ultimately prolonging their stay in the market [33]. GG is a cost-effective multivitamin that is ideal for use in the production of sweets and jams due to its high crystallinity and its capacity to regulate the product's moisture. Not only is the gel colorless and has a high melting point but sweets can also be stored at room temperature. Research has shown that the optimal concentration for sweets is 0.3%. Foods with GG can retain their shape and appearance for an extended period due to its water-absorbing properties [34]. In a study, Kong et al. [35] discovered that incorporating 0.1% of low-acyl GG into soybean milk yogurt resulted in the development of a stable gel network with increased viscosity, enhanced water retention capacity, and a smoother texture in comparison to the control group. Thus, GG is regarded as a stabilizer. It is appropriate for this product while also enhancing its sensory characteristics. In a study by Mongkontanawat and Khunphutthiraphi [36], it was found that incorporating 10% GG into sprouted black rice for vegetable yogurt resulted in a soft texture and good sensory appeal. This addition did not impact the moisture, protein, or fat content but also increased the levels of antioxidants and lactic acid bacteria. The study demonstrated significant toxicity toward breast cancer cell lines when compared to yogurt produced from sprouted rice without added GG [36]. This offers the opportunity to create nourishing and wholesome meals for adults and elderly people.

Production and Utilization of Edible Films

Edible films developed from GG have become increasingly popular in food-related uses because of their versatility and advantageous characteristics [12][37]. These films are thin layers of material that can be ingested with food, offering different functionalities. An overview of the production and applications of edible films using GG in the food industry is provided in **Table 2** and **Table 3**. Utilizing GG in edible films presents a sustainable and functional method for food-related uses, delivering advantages like decreased waste, enhanced preservation, and improved sensory experiences for consumers [12][15].

Table 2. Production of edible films using gellan gum [38][39][40].

Aspects of Edible Film Production	Remarks
Ingredient selection	GG has been chosen as the primary hydrocolloid for film formation. Additional components can be incorporated to improve the characteristics of the film, including plasticizers like glycerol and sorbitol, antimicrobial agents, antioxidants, or flavorings.
Solution preparation	GG is commonly dispersed in water or a water-based solution. Next, the solution is heated to fully hydrate and dissolve the GG.
Film formation	Once the solution is ready, it is poured or cast into a mold or onto a flat surface to create a thin layer. The film-forming solution can be dried using techniques such as air drying, hot air drying, or freeze-drying based on the desired properties of the film.
Control of film properties	By adjusting the concentration of GG and other additives along with the drying conditions, it is possible to control the properties of the edible film, including the thickness, transparency, and mechanical strength.

Table 3. Versatile applications of gellan gum-based edible films across various fields of food.

Multiple Applications within the Food Sector	Remarks	References
Food packaging	Edible films composed of GG are used as packaging for a variety of food items. These films serve as protective shields that block out moisture, oxygen, and other environmental elements, ultimately prolonging the shelf life of perishable items.	[41]
Coatings for fresh produce	Edible films developed from GG are suitable for coating fresh fruits and vegetables. The films aid in decreasing water loss and preserving	[42][43][44]

Multiple Applications within the Food Sector	Remarks	References
	freshness and can also be used to transport additional nutrients or preservatives.	
Encapsulation of bioactive compounds	GG films are ideal for encapsulating and protecting bioactive compounds like antioxidants, vitamins, or antimicrobial agents. This enables a regulated release of these substances within the food matrix.	[27][45][46]
Flavor films	GG-based films have the capability to incorporate flavors or aromas, offering a distinctive and personalized sensory encounter when utilized as coverings for candies, confections, or other flavored food items.	[47][48]
Edible strips and wrappers	GG films can be shaped into strips or wrappers that are convenient to use and eat. This is especially beneficial for products that require a thin, dissolvable layer, like single-serving condiment packets.	[49]
Improvement of texture	Edible films composed of GG have the potential to enhance the texture of specific food products, resulting in a more pleasing mouthfeel and improved crispiness.	[50][51]
Other innovative uses	Exploring GG-based edible films in different innovative applications such as edible food labels, decorations, and interactive food experiences.	[52]

lay a role medicinal also been employed to develop ointments to treat dental and ocular conditions [53]. To explore the gelatinous properties, Bajaj et al. [54] mixed GG with the antibiotic ciprofloxacin. Ciprofloxacin is an antibiotic that effectively targets both gram-negative and gram-positive aerobic bacteria. According to these results, the mixing process led to a longer duration of medication release in the body, enhancing the medicine's effectiveness against specific bacteria. Dev et al. [12] showed that a capsule produced with GG consisted of an ionic solution in the presence of water containing calcium ions. This solution formed a three-dimensional network of GG gel by creating intersections in the polymer chain caused by the presence of these ions. This led to the creation of a capsule that could be used to deliver the drug to humans.

Table 4. Examples of gellan gum-based micro and nanoparticulate systems.

Drug/Application Formulation	Fabrication Procedure	Most Important Type	Results	Reference
Model microgels	Ionotropic gelation with $CaCl_2$ or KCl, coating with chitosan	Microgels	Good stability in aqueous media except for KCl-crosslinked microgels; the particles were stable in gastric conditions; chitosan-coated microgels were less susceptible to degradation in intestinal fluid	[55]
Prednisolone, paclitaxel/cancer	Self-assembly	Nanogels	Prednisolone acted as a hydrophobic moiety in nanogel self-assembly; increased cytotoxic	[56]

Drug/Application Formulation	Fabrication Procedure	Most Important Type	Results	Reference
			efficacy towards different cancer cell lines	
Curcumin/cancer	Polyelectrolyte complexation	Nanogels	Prolonged curcumin release; good hemocompatibility and non-toxicity	[57]
Piroxicam/non-melanoma skin cancers	Self-assembly	Nanogels	Nanogels enhanced drug retention in the epidermis; nanogels permeated across the stratum corneum and released the drug in the viable epidermis	[58]
Probiotic bacteria/gut microbiota dysbiosis	Ionic crosslinking with $CaCl_2$, freeze-drying	Microcapsules	Improved survival rate during simulated gastrointestinal tract passage	[59]
Calendula officinalis extract/cosmetic applications	Ionotropic gelation with $CaCl_2$ (extrusion or emulsion	Microspheres	The size and entrapment efficiency of microspheres depended on the fabrication method	[60]

vhen it is with the oxidizing agent called sodium periodate, a study was carried out with the purpose of finding a solution to this issue. This led to the appearance of hardness in the gel, which in turn led to an increase in the amount of time that the drug was available within the body. Additionally, the use of GG as a binder resulted in an increase in the number of viable bacteria cells [61]. Silva et al. [62] observed that GG is an effective carrier biomaterial that also improves cell adhesion. Furthermore, they stated that the polymer was modified by including a peptide that was obtained from fibronectin, which is a glycoprotein that is formed outside of the cell cells. Additionally, in comparison to unmixed GG, this combination resulted in the multiplication of neural stem cells, and the results of this research demonstrated that it was successful in treating damage connected to the spinal cord. GG has been applied in the field of tissue engineering as well. As per research conducted by Vasile et al. [63], GG hydrogels were utilized as scaffolds for the regeneration of different tissues like bone and cartilage. The hydrogel’s capacity to replicate the extracellular matrix and offer mechanical support to the cells positions it as a prime choice for tissue engineering purposes. Aside from its function in drug delivery and tissue engineering, GG has also been utilized in wound healing. Alharbi et al. [64] explored the application of GG-based hydrogels in treating chronic wounds. The researchers discovered that the hydrogel supported wound healing by creating a moist environment that helped cells migrate and boosted angiogenesis. Moreover, GG has been investigated for its promise in the realm of regenerative medicine. An investigation conducted by Ghandforoushan et al. [65] showcased the application of GG hydrogels in transporting stem cells. The hydrogel created an optimal microenvironment for the stem cells, improving their ability to survive and differentiate, ultimately boosting their therapeutic capabilities. Furthermore, GG has been used in creating controlled-release dosage forms. A study conducted by Carrêlo et al. [66] reported the development of GG-based microparticles for the sustained release of drugs. The microparticles demonstrated a controlled release profile that enabled extended drug release and enhanced therapeutic effectiveness.

Responsive Systems for Biomedical Applications

GG, a highly versatile hydrocolloid, has been receiving increased interest in the biomedical sector because of its exceptional properties and potential uses in developing responsive systems [67][68]. There have been several cutting-edge advancements in the use of GG to develop responsive systems in the field of biomedical applications (**Table 5**). The latest developments in the use of GG in various biomedical fields demonstrate its ability to advance drug delivery [64][67][68][69], tissue engineering [70][71], wound healing [72][73], and diagnostics [68][74]. The responsive nature of GG enables the development of specific systems that react to particular physiological signals, enhancing their efficiency and flexibility in different biomedical scenarios.

Table 5. Innovative trends of utilizing gellan gum for the fabrication of responsive systems in biomedical applications.

Innovative Trend	Biomedical Application	References
Smart drug delivery systems	GG has been utilized in the development of advanced drug delivery systems that react to different stimuli, like temperature, pH, or specific ions. These systems can offer the controlled and targeted delivery of therapeutic substances, enhancing the effectiveness of drugs while reducing potential negative reactions	[64][67][68][69]
Temperature-responsive hydrogels	Hydrogels composed of GG have been formulated to demonstrate temperature-sensitive properties, enabling them to transition between sol and gel states based on temperature variations. This characteristic is especially valuable in scenarios where in situ gelation is required, like injectable hydrogels for minimally invasive drug delivery or tissue engineering.	[64][75][76]
Ion-responsive systems	GG can produce gels when exposed to certain ions, like calcium or potassium. This characteristic has been utilized in the creation of ion-responsive systems, which are designed to release drugs or bioactive agents in response to certain ions found in the body.	[77][78]
3D bioprinting and tissue engineering	When combined with other biomaterials, GG has been studied for its potential in 3D bioprinting for tissue engineering. Due to GG's capability of producing thermoreversible gels, it enables the development of intricate structures with improved mechanical characteristics, ideal for scaffold production.	[70][71][79][80]
Wound healing and dressings	Research has been conducted on hydrogels composed of GG for potential uses in promoting wound healing. These hydrogels offer a moist environment, strong adherence to the wound site, and the potential release of bioactive compounds to improve the healing process. Features can be integrated to cater to particular wound conditions.	[72][73]
Injectable systems for minimally invasive procedures	The thermoreversible gelation property of GG has been utilized to develop injectable systems for minimally invasive procedures. These systems have the capability to be administered in a liquid state and then undergo gelation in situ, which renders them ideal for various applications like tissue augmentation or local drug delivery.	[81][82][83]

Innovative Trend	Biomedical Application	References
Diagnostic applications	GG has been investigated for its use in producing diagnostic devices and biosensors. Utilizing the unique properties of GG, it is possible to develop sensing platforms capable of detecting particular biomolecules or variations in physiological conditions.	[68][69][71][74][84]
Combination with nanoparticles	GG can be combined with nanoparticles, like drug-loaded nanoparticles or imaging agents, to develop multifunctional responsive systems with improved therapeutic or diagnostic capabilities.	[79][85][86]

...s well as ...y at low ... as active ingredients. GG aims to enhance water retention and alter rheological characteristics [87]. GG is a key component in numerous cosmetics, serving to enhance viscosity and act as a stabilizer for certain emulsions applied to and left on the skin. It has been utilized in concentrations ranging from 0.3% to 0.5%. It can also be utilized in the production of toothpaste at concentrations ranging from 0.025% to 0.25%. These minimal amounts provide durability to the product even at temperatures as high as 60 °C, along with its thin texture and uniformity [88]. In a study by Iurciuc et al. [89], it was discovered that GG has positive effects on cosmetics, particularly in hair moisturizing and sun protection products. When GG is applied to the skin, it provides a pleasant sensation to the user. It was combined with xanthan gum to enhance the effectiveness of hair care products, being utilized at a concentration of 0.2%.

2.4. Biological Applications

GG, derived from bacteria, has been utilized as a substitute for agar in fields for cultivating various microorganisms. It has been introduced to the market as Gelrite because certain microorganisms have specific enzymes that can break down agarose into the compound 3,6-anhydro. L-galactose and D-galactose are indicated in reference [90]. GG was developed under a different brand name, phyta gel, and is commonly utilized as a replacement for agar in agricultural media. It also helps in solidifying the agricultural media for growing tissue plants [91]. GG was utilized for the separation of DNA components post-extraction from various sources through electrophoresis. It acts as a gel with pores, enabling the passage of these components [92].

References

1. Ahmed, E.M. Hydrogel: Preparation, characterization, and applications: A review. J. Adv. Res. 2015, 6, 105–121.
2. Tanaka, F. Theoretical study of molecular association and thermoreversible gelation in polymers. Polym. J. 2002, 34, 479–509.
3. Yang, L.; Han, Z.; Chen, C.; Li, Z.; Yu, S.; Qu, Y.; Zeng, R. Novel probiotic-bound oxidized Bletilla striata polysaccharide-chitosan composite hydrogel. Mater. Sci. Eng. C 2020, 117, 111265.
4. Yang, X.; Gong, T.; Lu, Y.H.; Li, A.; Sun, L.; Guo, Y. Compatibility of sodium alginate and konjac glucomannan and their applications in fabricating low-fat mayonnaise-like emulsion gels. Carbohydr. Polym. 2020, 229, 115468.

5. Shahbazizadeh, S.; Naji-Tabasi, S.; Shahidi-Noghabi, M.; Pourfarzad, A. Development of cress seed gum hydrogel and investigation of its potential application in the delivery of curcumin. J. Sci. Food Agric. 2021, 101, 6505–6513.
6. Wang, X.; Goff, H.D.; Cui, S.W. Comparison of synergistic interactions of yellow mustard gum with locust bean gum or κ-carrageenan. Food Hydrocoll. 2022, 132, 107804.
7. Cairns, P.; Miles, M.J.; Morris, V.J.; Brownsey, G.J. X-ray fibre-diffraction studies of synergistic, binary polysaccharide gels. Carbohydr. Res. 1987, 160, 411–423.
8. Xu, X.; Li, B.; Kennedy, J.F.; Xie, B.J.; Huang, M. Characterization of konjac glucomannan–gellan gum blend films and their suitability for release of nisin incorporated therein. Carbohydr. Polym. 2007, 70, 192–197.
9. Wu, C.; Peng, S.; Wen, C.; Wang, X.; Fan, L.; Deng, R.; Pang, J. Structural characterization and properties of konjac glucomannan/curdlan blend films. Carbohydr. Polym. 2012, 89, 497–503.
10. de Souza, C.F.; Riegel-Vidotti, I.C.; Cardoso, M.B.; Ono, L.; Lucyszyn, N.; Lubambo, A.F.; Sens, C.V.; Grein-Iankovski, A.; Sierakowski, M.R. Nanometric organisation in blends of gellan/xyloglucan hydrogels. Carbohydr. Polym. 2014, 114, 48–56.
11. Tao, H.; Wang, B.; Wen, H.; Cui, B.; Zhang, Z.; Kong, X.; Wang, Y. Improvement of the textural characteristics of curdlan gel by the formation of hydrogen bonds with erythritol. Food Hydrocoll. 2021, 117, 106648.
12. Dev, M.J.; Warke, R.G.; Warke, G.M.; Mahajan, G.B.; Patil, T.A.; Singhal, R.S. Advances in fermentative production, purification, characterization and applications of gellan gum. Bioresour. Technol. 2022, 359, 127498.
13. Rühmann, B.; Schmid, J.; Sieber, V. Methods to identify the unexplored diversity of microbial exopolysaccharides. Front. Microbiol. 2015, 6, 565.
14. Fialho, A.M.; Moreira, L.M.; Granja, A.T.; Popescu, A.O.; Hoffmann, K.; Sá-Correia, I. Occurrence, production, and applications of gellan: Current state and perspectives. Appl. Microbiol. Biotechnol. 2008, 79, 889–900.
15. Raghunandan, K.; Kumar, A.; Kumar, S.; Permaul, K.; Singh, S. Production of gellan gum, an exopolysaccharide, from biodiesel-derived waste glycerol by Sphingomonas spp. 3 Biotech 2018, 8, 71.
16. Huang, J.; Zhu, S.; Li, C.; Zhang, C.; Ji, Y. Cost-effective optimization of gellan gum production by Sphingomonas paucimobilis using corn steep liquor. Prep. Biochem. Biotechnol. 2020, 50, 191–197.
17. Wang, D.; Kim, H.; Lee, S.; Kim, D.H.; Joe, M.H. Improved gellan gum production by a newly-isolated Sphingomonas azotifigens GL-1 in a cheese whey and molasses based medium.

Process Biochem. 2020, 95, 269–278.

18. Bagheri, L.; Mousavi, M.E.; Madadlou, A. Stability and rheological properties of suspended pulp particles containing orange juice stabilized by gellan gum. J. Dispers. Sci. Technol. 2014, 35, 1222–1229.
19. Saha, D.; Bhattacharya, S. Characteristics of gellan gum-based food gels. J. Texture Stud. 2010, 41, 459–471.
20. Sworn, G.; Stouby, L. Gellan gum. In Handbook of Hydrocolloids; Woodhead Publishing: Sawston, UK, 2021; pp. 855–885.
21. EFSA Panel on Food Additives and Nutrient Sources added to Food (ANS); Younes, M.; Aggett, P.; Aguilar, F.; Crebelli, R.; Filipic, M.; Frutos, M.J.; Frutos, P.; Gott, D.; Gundert-Remy, U.; et al. Re-evaluation of gellan gum (E 418) as food additive. EFSA J. 2018, 16, e05296.
22. Chen, B.; Cai, Y.; Liu, T.; Huang, L.; Zhao, X.; Zhao, M.; Deng, X.; Zhao, Q. Formation and performance of high acyl gellan hydrogel affected by the addition of physical-chemical treated insoluble soybean fiber. Food Hydrocoll. 2020, 101, 105526.
23. Stephen, A.M.; Phillips, G.O. Food Polysaccharides and Their Applications; CRC Press: Boca Raton, FL, USA, 2016.
24. Jin, H.; Lee, N.K.; Shin, M.K.; Kim, S.K.; Kaplan, D.L.; Lee, J.W. Production of gellan gum by Sphingomonas paucimobilis NK2000 with soybean pomace. Biochem. Eng. J. 2003, 16, 357–360.
25. Martins, L.O.; Sá-Correia, I. Temperature profiles of gellan gum synthesis and activities of biosynthetic enzymes. Biotechnol. Appl. Biochem. 1994, 20, 385–395.
26. Miyoshi, E.; Nishinari, K. Rheological and thermal properties near the sol-gel transition of gellan gum aqueous solutions. In Physical Chemistry and Industrial Application of Gellan Gum; Nishinari, K., Ed.; Springer: Berlin/Heidelberg, Germany, 1999; pp. 68–82.
27. Zhang, H.; Zhang, F.; Yuan, R. Applications of natural polymer-based hydrogels in the food industry. In Hydrogels Based on Natural Polymers; Elsevier: Amsterdam, The Netherlands, 2020; pp. 357–410.
28. Sharma, S.; Bhende, M.; Goel, A. A review: Polysaccharide-based hydrogels and their biomedical applications. Polym. Bull. 2024, 1–22.
29. Fialho, A.M.; Martins, L.O.; Donval, M.L.; Leitão, J.H.; Ridout, M.J.; Jay, A.J.; Morris, V.J.; Sá-Correia, I. Structures and properties of gellan polymers produced by Sphingomonas paucimobilis ATCC 31461 from lactose compared with those produced from glucose and from cheese whey. Appl. Environ. Microbiol. 1999, 65, 2485–2491.
30. Choudhury, A.R. Synthesis and rheological characterization of a novel thermostable quick setting composite hydrogel of gellan and pullulan. Int. J. Biol. Macromol. 2019, 125, 979–988.

31. Kanyuck, K.M.; Norton-Welch, A.B.; Mills, T.B.; Norton, I.T. Structural characterization of interpenetrating network formation of high acyl gellan and maltodextrin gels. Food Hydrocoll. 2021, 112, 106295.
32. Sapper, M.; Bonet, M.; Chiralt, A. Wettability of starch-gellan coatings on fruits, as affected by the incorporation of essential oil and/or surfactants. LWT 2019, 116, 108574.
33. Leal, A.R.; Oliveira, L.D.S.; Costa, J.N.D.; Alves, C.A.N.; Mata, P.; Sousa, P.H.M.D. In vitro bioaccessibility of antioxidant compounds from structured fruits developed with gellan gum and agar. Rev. Cienc. Agron. 2022, 53, e20207744.
34. Iurciuc, C.; Savin, A.; Lungu, C.; Martin, P.; Popa, M. Gellan. food applications. Cellul. Chem. Technol. 2016, 13, 1–13.
35. Kong, X.; Xiao, Z.; Du, M.; Wang, K.; Yu, W.; Chen, Y.; Liu, Z.; Cheng, Y.; Gan, J. Physicochemical, Textural, and Sensorial Properties of Soy Yogurt as Affected by Addition of Low Acyl Gellan Gum. Gels 2022, 8, 453.
36. Mongkontanawat, N.; Khunphutthiraphi, T. Improved sensory acceptance and cytotoxicity to breast cancer cell line of instant germinated black rice yogurt supplemented with gellan gum. Food Agric. Sci. Technol. 2022, 8, 15–29.
37. Giavasis, I.; Harvey, L.M.; McNeil, B. Gellan gum. Crit. Rev. Biotechnol. 2000, 20, 177–211.
38. Xiao, G.; Zhu, Y.; Wang, L.; You, Q.; Huo, P.; You, Y. Production and storage of edible film using gellan gum. Procedia Environ. Sci. 2011, 8, 756–763.
39. Alizadeh-Sani, M.; Ehsani, A.; Moghaddas Kia, E.; Khezerlou, A. Microbial gums: Introducing a novel functional component of edible coatings and packaging. Appl. Microbiol. Biotechnol. 2019, 103, 6853–6866.
40. Zikmanis, P.; Juhņeviča-Radenkova, K.; Radenkovs, V.; Segliņa, D.; Krasnova, I.; Kolesovs, S.; Orlovskis, Z.; Šilaks, A.; Semjonovs, P. Microbial polymers in edible films and coatings of garden berry and grape: Current and prospective use. Food Bioprocess Technol. 2021, 14, 1432–1445.
41. Moghadam, F.A.M.; Khoshkalampour, A.; Moghadam, F.A.M.; PourvatanDoust, S.; Naeijian, F.; Ghorbani, M. Preparation and physicochemical evaluation of casein/basil seed gum film integrated with guar gum/gelatin based nanogel containing lemon peel essential oil for active food packaging application. Int. J. Biol. Macromol. 2023, 224, 786–796.
42. Tahir, H.E.; Xiaobo, Z.; Mahunu, G.K.; Arslan, M.; Abdalhai, M.; Zhihua, L. Recent developments in gum edible coating applications for fruits and vegetables preservation: A review. Carbohydr. Polym. 2019, 224, 115141.
43. Maurizzi, E.; Bigi, F.; Volpelli, L.A.; Pulvirenti, A. Improving the post-harvest quality of fruits during storage through edible packaging based on guar gum and hydroxypropyl methylcellulose. Food

Packag. Shelf Life 2023, 40, 101178.

44. Yang, Z.; Li, C.; Wang, T.; Li, Z.; Zou, X.; Huang, X.; Zhai, X.; Shi, J.; Shen, T.; Gong, Y.; et al. Novel gellan gum-based probiotic film with enhanced biological activity and probiotic viability: Application for fresh-cut apples and potatoes. Int. J. Biol. Macromol. 2023, 239, 124128.
45. Taheri, A.; Jafari, S.M. Gum-based nanocarriers for the protection and delivery of food bioactive compounds. Adv. Colloid Interface Sci. 2019, 269, 277–295.
46. Chaudhary, V.; Thakur, N.; Kajla, P.; Thakur, S.; Punia, S. Application of encapsulation technology in edible films: Carrier of bioactive compounds. Front. Sustain. Food Syst. 2021, 5, 734921.
47. Gupta, V.; Biswas, D.; Roy, S. A comprehensive review of biodegradable polymer-based films and coatings and their food packaging applications. Materials 2022, 15, 5899.
48. Jiang, H.; Zhang, W.; Chen, L.; Liu, J.; Cao, J.; Jiang, W. Recent advances in guar gum-based films or coatings: Diverse property enhancement strategies and applications in foods. Food Hydrocoll. 2023, 136, 108278.
49. Yang, L. Physicochemical Properties of Biodegradable/Edible Films Made with Gellan Gum; DalTech-Dalhousie University: Halifax, NS, Canada, 1999.
50. Rafe, A. Improving Texture of Foods using Emerging Hydrocolloids. Emerg. Nat. Hydrocoll. Rheol. Funct. 2019, 20, 499–523.
51. Yang, X.; Li, A.; Li, X.; Sun, L.; Guo, Y. An overview of classifications, properties of food polysaccharides and their links to applications in improving food textures. Trends Food Sci. Technol. 2020, 102, 1–15.
52. Mahmoud, Y.A.G.; El-Naggar, M.E.; Abdel-Megeed, A.; El-Newehy, M. Recent advancements in microbial polysaccharides: Synthesis and applications. Polymers 2021, 13, 4136.
53. Muthukumar, T.; Song, J.E.; Khang, G. Biological role of gellan gum in improving scaffold drug delivery, cell adhesion properties for tissue engineering applications. Molecules 2019, 24, 4514.
54. Bajaj, I.B.; Saudagar, P.S.; Singhal, R.S.; Pandey, A. Statistical approach to optimization of fermentative production of gellan gum from Sphingomonas paucimobilis ATCC 31461. J. Biosci. Bioeng. 2006, 102, 150–156.
55. Vilela, J.A.P.; de Assis Perrechil, F.; Picone, C.S.F.; Sato, A.C.K.; da Cunha, R.L. Preparation, characterization and in vitro digestibility of gellan and chitosan–gellan microgels. Carbohydr. Polym. 2015, 117, 54–62.
56. D’Arrigo, G.; Navarro, G.; Di Meo, C.; Matricardi, P.; Torchilin, V. Gellan gum nanohydrogel containing anti-inflammatory and anti-cancer drugs: A multi-drug delivery system for a combination therapy in cancer treatment. Eur. J. Pharm. Biopharm. 2014, 87, 208–216.

57. Mahajan, H.S.; Patil, P.P. In situ cross linked chitosan-gellan gum polyelectrolyte complex based nanogels containing curcumin for delivery to cancer cells. Indian J. Pharm. Educ. Res. 2017, 51, s40–s45.

58. Musazzi, U.M.; Cencetti, C.; Franzé, S.; Zoratto, N.; Di Meo, C.; Procacci, P.; Matricardi, P.; Cilurzo, F. Gellan nanohydrogels: Novel nanodelivery systems for cutaneous administration of piroxicam. Mol. Pharm. 2018, 15, 1028–1036.

59. Marcial-Coba, M.S.; Cieplak, T.; Cahú, T.B.; Blennow, A.; Knøchel, S.; Nielsen, D.S. Viability of microencapsulated Akkermansia muciniphila and Lactobacillus plantarum during freeze-drying, storage and in vitro simulated upper gastrointestinal tract passage. Food Funct. 2018, 9, 5868–5879.

60. Kozlowska, J.; Prus-Walendziak, W.; Stachowiak, N.; Bajek, A.; Kazmierski, L.; Tylkowski, B. Modification of collagen/gelatin/hydroxyethyl cellulose-based materials by addition of herbal extract-loaded microspheres made from gellan gum and xanthan gum. Materials 2020, 13, 3507.

61. Gong, Y.; Wang, C.; Lai, R.C.; Su, K.; Zhang, F.; Wang, D.A. An improved injectable polysaccharide hydrogel: Modified gellan gum for long-term cartilage regeneration in vitro. J. Mater. Chem. 2009, 19, 1968–1977.

62. Silva, N.A.; Cooke, M.J.; Tam, R.Y.; Sousa, N.; Salgado, A.J.; Reis, R.L.; Shoichet, M.S. The effects of peptide modified gellan gum and olfactory ensheathing glia cells on neural stem/progenitor cell fate. Biomaterials 2012, 33, 6345–6354.

63. Vasile, C.; Pamfil, D.; Stoleru, E.; Baican, M. New developments in medical applications of hybrid hydrogels containing natural polymers. Molecules 2020, 25, 1539.

64. Alharbi, H.Y.; Alnoman, R.B.; Aljohani, M.S.; Al-Anazia, M.; Monier, M. Synthesis and characterization of gellan gum-based hydrogels for drug delivery applications. Int. J. Biol. Macromol. 2024, 258, 128828.

65. Ghandforoushan, P.; Alehosseini, M.; Golafshan, N.; Castilho, M.; Dolatshahi-Pirooz, A.; Hanaee, J.; Davaran, S.; Orive, G. Injectable hydrogels for cartilage and bone tissue regeneration: A review. Int. J. Biol. Macromol. 2023, 246, 125674.

66. Carrêlo, H.; Cidade, M.T.; Borges, J.P.; Soares, P. Gellan gum/alginate microparticles as drug delivery vehicles: DOE production optimization and drug delivery. Pharmaceuticals 2023, 16, 1029.

67. Nayak, A.K.; Hasnain, M.S. (Eds.) Advanced Biopolymeric Systems for Drug Delivery; Springer: Cham, Switzerland, 2020; pp. 373–384.

68. Shymborska, Y.; Budkowski, A.; Raczkowska, J.; Donchak, V.; Melnyk, Y.; Vasiichuk, V.; Stetsyshyn, Y. Switching it Up: The Promise of Stimuli-Responsive Polymer Systems in Biomedical Science. Chem. Rec. 2023, 24, e202300217.

69. Garcia, M.T.; Carmo, P.H.F.d.; Figueiredo-Godoi, L.M.A.; Gonçalves, N.I.; Lima, P.M.N.d.; Ramos, L.d.P.; Oliveira, L.D.d.; Borges, A.L.S.; Shukla, A.; Junqueira, J.C. Gellan-Based Hydrogel as a Drug Delivery System for Caffeic Acid Phenethyl Ester in the Treatment of Oral Candida albicans Infections. Pharmaceutics 2024, 16, 298.

70. Akkineni, A.R.; Ahlfeld, T.; Funk, A.; Waske, A.; Lode, A.; Gelinsky, M. Highly concentrated alginate-gellan gum composites for 3D plotting of complex tissue engineering scaffolds. Polymers 2016, 8, 170.

71. Wu, S.; Xiao, R.; Wu, Y.; Xu, L. Advances in tissue engineering of gellan gum-based hydrogels. Carbohydr. Polym. 2023, 324, 121484.

72. Feketshane, Z.; Alven, S.; Aderibigbe, B.A. Gellan gum in wound dressing scaffolds. Polymers 2022, 14, 4098.

73. Bal-Öztürk, A.; Torkay, G.; İdil, N.; Özkahraman, B.; Özbaş, Z. Gellan gum/guar gum films incorporated with honey as potential wound dressings. Polym. Bull. 2024, 81, 1211–1228.

74. Ramaprabha, K.; Kumar, V.; Saravanan, P.; Rajeshkannan, R.; Rajasimman, M.; Kamyab, H.; Vasseghian, Y. Exploring the diverse applications of Carbohydrate macromolecules in food, pharmaceutical, and environmental technologies. Environ. Res. 2024, 240, 117521.

75. Mousavi, S.S.; Keshvari, H.; Daemi, H. Partial sulfation of gellan gum produces cytocompatible, body temperature-responsive hydrogels. Int. J. Biol. Macromol. 2023, 235, 123525.

76. Xu, S.Q.; Du, Y.N.; Zhang, Z.J.; Yan, J.N.; Sun, J.J.; Zhang, L.C.; Wang, C.; Lai, B.; Wu, H.T. Gel properties and interactions of hydrogels constructed with low acyl gellan gum and puerarin. Carbohydr. Polym. 2024, 326, 121594.

77. Zhan, L.; Lan, G.; Wang, Y.; Xie, S.; Cai, S.; Liu, Q.; Chen, P.; Xie, F. Mastering textural control in multi-polysaccharide gels: Effect of κ-carrageenan, konjac glucomannan, locust bean gum, low-acyl gellan gum, and sodium alginate. Int. J. Biol. Macromol. 2024, 254, 127885.

78. Zhou, S.; Zheng, X.; Yi, K.; Du, X.; Wang, C.; Cui, P.; Jiang, P.; Ni, X.; Qiu, L.; Wang, J. Temperature-Ion-pH Triple Responsive Gellan Gum as In Situ Hydrogel for Long-Acting Cancer Treatment. Gels 2022, 8, 508.

79. Razali, M.H.; Ismail, N.A.; Zulkafli, M.F.A.M.; Amin, K.A.M. 3D Nanostructured materials: TiO2 nanoparticles incorporated gellan gum scaffold for photocatalyst and biomedical Applications. Mater. Res. Express 2018, 5, 035039.

80. Lameirinhas, N.S.; Teixeira, M.C.; Carvalho, J.P.; Valente, B.F.; Pinto, R.J.; Oliveira, H.; Luís, J.L.; Pires, P.L.; Oliveira, J.M.; Vilela, C.; et al. Nanofibrillated cellulose/gellan gum hydrogel-based bioinks for 3D bioprinting of skin cells. Int. J. Biol. Macromol. 2023, 229, 849–860.

81. Oliveira, J.T.; Santos, T.C.; Martins, L.; Picciochi, R.; Marques, A.P.; Castro, A.G.; Neves, N.M.; Mano, J.F.; Reis, R.L. Gellan gum injectable hydrogels for cartilage tissue engineering applications: In vitro studies and preliminary in vivo evaluation. Tissue Eng. Part A 2010, 16, 343–353.
82. Pacelli, S.; Paolicelli, P.; Dreesen, I.; Kobayashi, S.; Vitalone, A.; Casadei, M.A. Injectable and photocross-linkable gels based on gellan gum methacrylate: A new tool for biomedical application. Int. J. Biol. Macromol. 2015, 72, 1335–1342.
83. Posadowska, U.; Brzychczy-Włoch, M.; Drożdż, A.; Krok-Borkowicz, M.; Włodarczyk-Biegun, M.; Dobrzyński, P.; Chrzanowski, W.; Pamuła, E. Injectable hybrid delivery system composed of gellan gum, nanoparticles and gentamicin for the localized treatment of bone infections. Expert Opin. Drug Deliv. 2016, 13, 613–620.
84. Cho, H.H.; Choi, J.H.; Been, S.Y.; Kim, N.; Choi, J.M.; Kim, W.; Kim, D.; Jung, J.J.; Song, J.E.; Khang, G. Development of fluorescein isothiocyanate conjugated gellan gum for application of bioimaging for biomedical application. Int. J. Biol. Macromol. 2020, 164, 2804–2812.
85. Pacelli, S.; Paolicelli, P.; Moretti, G.; Petralito, S.; Di Giacomo, S.; Vitalone, A.; Casadei, M.A. Gellan gum methacrylate and laponite as an innovative nanocomposite hydrogel for biomedical applications. Eur. Polym. J. 2016, 77, 114–123.
86. Nayak, A.K.; Bera, H.; Hasnain, M.S.; De, A.; Pal, D.; Samanta, A. Gellan gum-based nanomaterials in drug delivery applications. In Biopolymer-Based Nanomaterials in Drug Delivery and Biomedical Applications; Academic Press: Cambridge, MA, USA, 2021; pp. 313–336.
87. Freitas, F.; Alves, V.D.; Reis, M.A. Bacterial polysaccharides: Production and applications in cosmetic industry. In Polysaccharides; Springer: Cham, Switzerland, 2015; pp. 2017–2043.
88. Prajapati, V.D.; Jani, G.K.; Zala, B.S.; Khutliwala, T.A. An insight into the emerging exopolysaccharide gellan gum as a novel polymer. Carbohydr. Polym. 2013, 93, 670–678.
89. Iurciuc, C.E.; Lungu, C.; Martin, P.; Popa, M. Gellan. Pharmaceutical, medical and cosmetic applications. Cellul. Chem Technol. 2017, 51, 187–202.
90. Lee, C.H.; Kim, H.T.; Yun, E.J.; Lee, A.R.; Kim, S.R.; Kim, J.H.; Choi, I.G.; Kim, K.H. A novel agarolytic β-galactosidase acts on agarooligosaccharides for complete hydrolysis of agarose into monomers. Appl. Environ. Microbiol. 2014, 80, 5965–5973.
91. Sanchez-Cardozo, J.; Quintanilla-Carvajal, M.X.; Ruiz-Pardo, R.; Acosta-González, A. Evaluating gelling-agent mixtures as potential substitutes for bacteriological agar: An approach by mixture design. Dyna 2019, 86, 171–176.
92. Descallar, F.B.A.; Matsukawa, S. Change of network structure in agarose gels by aging during storage studied by NMR and electrophoresis. Carbohydr. Polym. 2020, 245, 116497.