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REVIEW ARTICLE
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# NATURAL POLYMER EXCIPIENTS: A GREEN APPROACH TO MULTIFUNCTIONALITY IN DRUG FORMULATION

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**ABSTRACT**

Natural polymer excipients are increasingly recognized as sustainable and multifunctional green alternatives to synthetic ones in pharmaceutical formulations. They not only provide safe, biocompatible, and renewable materials for drug delivery but also align with green pharmacy principles by reducing reliance on non-renewable, petroleum-based excipients. Polysaccharides such as cellulose derivatives, starches, chitosan, alginate, and pectin exhibit multifunctional roles as binders, disintegrants, controlled-release matrices, stabilizers, film formers, and mucoadhesive agents. Protein-based polymers like gelatin and collagen further contribute bioactive, tissue-compatible, and hemostatic properties, making them excellent eco-friendly excipients. By enabling multiple functions within a single material, natural polymers promote formulation simplification, cost-effectiveness, and enhanced therapeutic outcomes while reducing environmental burden throughout the product life cycle.

Green approaches like enzymatic modification, biotechnological production, and eco-friendly processing techniques have expanded their potential while minimizing chemical waste and energy consumption. The use of hybrid systems, artificial intelligence, and green synthesis technologies further strengthens their performance and environmental adaptability. Natural polymers are therefore central to advancing sustainable pharmaceutical manufacturing, promoting eco-friendly healthcare, and supporting innovative, personalized, and patient-friendly formulations. This green approach ensures that these excipients not only enhance therapeutic efficiency but also align with environmental sustainability goals for next-generation drug delivery systems.

**KEYWORDS:** Natural Polymer Excipients, Green Chemistry, Multifunctional Polymers, Challenges, Recent Advances, Future Perspectives

## 1. INTRODUCTION

The pharmaceutical industry is increasingly shifting toward eco-friendly and sustainable practices to address the growing concerns of environmental impact, resource depletion, and patient safety. In this context, natural polymer excipients have emerged as promising green alternatives to conventional synthetic excipients traditionally derived from petroleum-based sources. Their renewable origin, inherent biocompatibility, and biodegradable nature make them not only safe and versatile but also aligned with the principles of green pharmacy [1].

Natural polymers such as polysaccharides (cellulose derivatives, starches, chitosan, alginate, pectin) and protein-based materials (gelatin, collagen) exhibit remarkable multifunctionality in pharmaceutical formulations. They can serve simultaneously as binders, disintegrants, stabilizers, film formers, controlled-release matrices, and mucoadhesive agents, thereby offering formulation efficiency and therapeutic advantages. The multifunctional nature of these materials also reduces the need for multiple excipients in a single dosage form, simplifying processing and lowering costs while minimizing environmental burdens [2].

Moreover, natural polymers enable innovative drug delivery mechanisms including pH-responsive release, site-specific targeting, mucoadhesion-enhanced retention, and antimicrobial protection. Advanced green technologies such as enzymatic modification, biotechnology-driven production, and hybrid system development continue to expand their physicochemical and functional properties. This aligns with sustainable manufacturing trends that emphasize reduced chemical waste, energy efficiency, and eco-friendly processing techniques [3].

Despite these advantages, challenges such as variability in raw materials, issues with standardization, and process optimization remain critical hurdles for their wide-scale adoption. Addressing these concerns through robust quality control and supportive regulatory frameworks is vital to fully harness their potential [4].

This review aims to provide a comprehensive overview of natural polymer excipients as green, multifunctional components in drug formulations, highlighting their sources, roles, technological advancements, and future prospects in sustainable pharmaceutical development [5].

### 1.1. Natural Polymer: Sources and Sustainability

Natural polymers utilized as pharmaceutical excipients originate from diverse biological sources including terrestrial plants, marine organisms, and microbial fermentation processes. Plant-derived polymers such as cellulose, starch, and pectin represent the most abundant renewable resources, offering consistent availability and established extraction technologies. Marine sources provide unique polysaccharides including alginate, carrageenan, and chitosan with specialized functional properties [6].

Microbial fermentation produces sophisticated polysaccharides such as xanthan gum, gellant gum, and dextran through controlled bioprocessing. These biotechnological approaches enable production of high-purity polymers with consistent properties while utilizing renewable substrates. The scalability of microbial production supports commercial pharmaceutical applications while maintaining sustainability principles [7].

Agricultural waste valorisation represents an emerging approach to natural polymer production, converting byproducts into valuable pharmaceutical excipients. Citrus peel waste provides pectin, while agricultural residues yield cellulose and modified starches [8]. This approach addresses waste management challenges while providing cost-effective raw materials for sustainable pharmaceutical manufacturing [9].

## 2. Classification of Natural Polymer as Excipients

Natural polymer excipients can be systematically classified based on their biological sources, chemical structures, and functional properties. This classification system facilitates better understanding of their characteristics and appropriate selection for specific pharmaceutical applications [10].

### 2.1 Source-Based Classification

Natural polymers are primarily derived from four major sources: plant materials, animal tissues, microbial fermentation, and marine organisms. Each source category exhibits distinct characteristics and processing requirements [11].

#### Plant-derived polymers

represent the largest category, encompassing cellulose derivatives, plant gums, mucilage’s modified starches. These polymers are abundant, renewable, and generally exhibit excellent safety profiles due to their long history of human consumption [12].

**Animal-derived polymers**
include proteins such as gelatin, casein, and chitosan (derived from crustacean shells), offering unique properties like thermos reversible gelation and mucoadhesion [13].

**Microbial polymers**
are produced through controlled fermentation processes, providing consistent quality and reduced contamination risks compared to directly extracted natural polymers [14].

**Marine-derived polymers**
such as alginate and carrageenan exhibit distinctive gelling properties and biocompatibility, making them valuable for specialized applications [15].
*Polymers can be classified in various ways, including by their chemical structure, source, molecular forces and polymerisation.

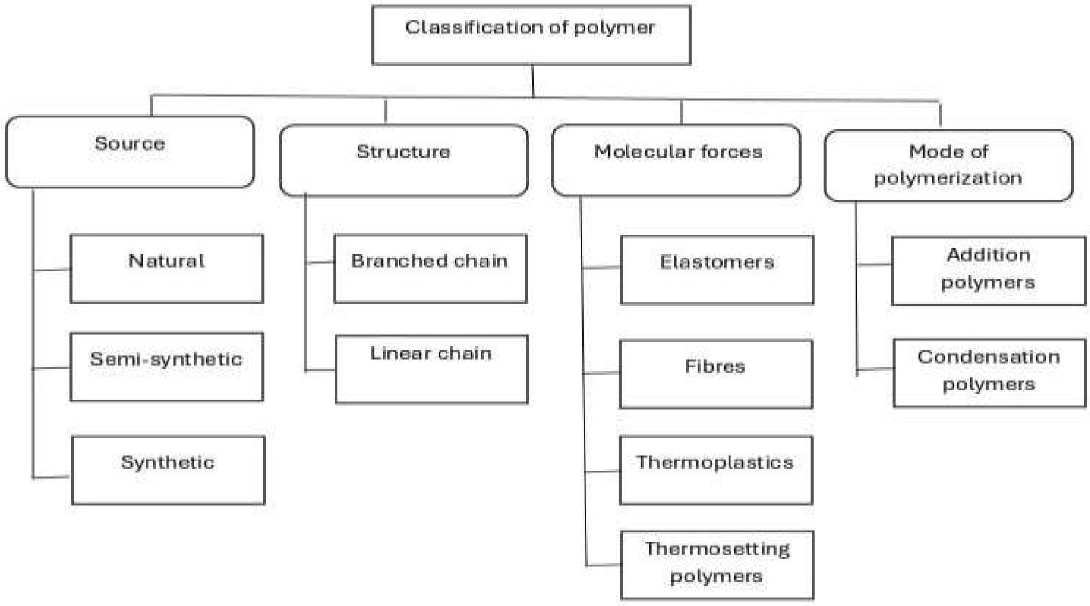


**Fig 1: Classification of polymers**

**Table 1:** Common Natural Polymers Used as Multifunctional Pharmaceutical Excipients

| Polymer | Source | Primary Functions | Green Benefits |
|---|---|---|---|
| Cellulose (MCC) | Plant cell walls | Binder, disintegrant, filler | Renewable, biodegradable |
| HPMC | Modified cellulose | Matrix former, film coating | Low toxicity, sustainable |
| CMC | Modified cellulose | Disintegrant, suspending agen | Water soluble, safe |
| Starch | Cereals/tubers | Binder, disintegrant, filler | Abundant, cost-effective |
| Chitosan | Crustacean shells | Mucoadhesive, antimicrobial | Antimicrobial, bioactive |
| Alginate | Brown seaweed | Controlled release, gelling | Marine renewable, safe |
| Pectin | Citrus peels | Colon targeting, emulsifier | Waste valorization |
| Xanthan Gum | Bacterial fermentation | Thickener, stabilizer | Fermentation-based |
| Gelatin | Animal collagen | Encapsulation, gelling | Biocompatible, natural |
| Collagen | Animal tissue | Injectable matrix, hemostasis | Bioactive, degradable |

## 3. Green Chemistry in Pharmaceutical Manufacturing

The pharmaceutical industry has increasingly embraced green chemistry principles to address environmental sustainability challenges while maintaining therapeutic efficacy and safety standards. Green chemistry focuses on designing chemical processes and products that minimize environmental impact through reduced waste generation, energy consumption, and hazardous substance utilization. In pharmaceutical excipient development, this approach emphasizes renewable resource utilization, biodegradable components, and environmentally benign processing methods [16].

Traditional pharmaceutical excipients, predominantly synthetic in origin, present environmental concerns including non-biodegradability, fossil fuel dependence, and energy-intensive production processes. The pharmaceutical sector contributes significantly to global carbon emissions, generating approximately 55% more emissions than the automotive industry. This environmental burden necessitates fundamental shifts toward sustainable manufacturing practices, particularly in excipient selection and utilization [17].

Natural polymer excipients represent a paradigmatic application of green chemistry principles in pharmaceutical formulation. These materials, derived from renewable biological sources, offer inherent advantages including biodegradability, biocompatibility, and reduced environmental persistence compared to synthetic alternatives. The integration of natural polymers supports circular economy principles while maintaining pharmaceutical performance standards [18].

### 3.1. Multifunctionality Concept in Excipient Design

Multifunctional excipients represent an innovative approach to pharmaceutical formulation that consolidates multiple essential functions within single components, addressing modern pharmaceutical challenges including cost containment, formulation complexity, and regulatory requirements. Traditional excipient systems often require numerous individual components to achieve desired functionality, resulting in complex formulations with increased risks of incompatibilities and manufacturing challenges [19].

The multifunctional approach enables pharmaceutical scientists to develop sophisticated drug delivery systems using fewer components while maintaining or enhancing therapeutic performance. Natural polymers demonstrate exceptional suitability for multifunctional applications due to their diverse molecular structures, multiple functional groups, and responsive behaviour to environmental conditions. These characteristics enable single natural polymers to perform roles traditionally requiring multiple synthetic excipients [20].

Economic and regulatory advantages of multifunctional excipients include reduced raw material costs, simplified manufacturing processes, streamlined quality control requirements, and faster regulatory approval through established safety profiles. The consolidation of functions reduces formulation complexity while improving manufacturing efficiency and product consistency [21].

## 4. Multifunctional Roles in Drug Formulation

### 4.1 Solid Dosage Form Applications

Natural polymer excipients in tablet formulations demonstrate exceptional multifunctionality by consolidating multiple essential functions within environmentally sustainable platforms [22]. Microcrystalline cellulose exemplifies green multifunctional design by serving as binder, disintegrant, and filler simultaneously, reducing formulation complexity while maintaining renewable resource utilization. The concentration-dependent functionality enables optimization for specific therapeutic requirements without requiring additional synthetic excipients [23].

Hydroxypropyl methylcellulose provides sophisticated controlled release functionality while serving as binder and film former, creating sustainable matrix tablets with predictable drug release profiles. The hydrophilic nature enables controlled drug release through gel layer formation while biodegradable characteristics ensure environmental safety after disposal [24].

This multifunctional approach significantly reduces the environmental impact of sustained release formulations [25].

### 4.2 Liquid and Semi-solid Formulations

Natural polymer excipients in liquid formulations provide integrated stabilization systems that combine thickening, suspending, emulsifying, and preservative functions within environmentally sustainable platforms. Xanthan gum demonstrates exceptional multifunctional capabilities by providing rheological control, suspension stability, and emulsion stabilization while being produced through sustainable fermentation processes [26].

Chitosan-based liquid formulations offer antimicrobial preservation, mucoadhesive enhancement, and penetration improvement functions while maintaining biocompatibility and biodegradability. The multifunctional nature eliminates the need for synthetic preservatives and penetration enhancers, creating more sustainable formulation systems. These green approaches address environmental concerns while maintaining pharmaceutical performance standards [27].

**Table 2: Multifunctional Applications in Various Dosage Form**

| Dosage Form | Natural Polymers | Functions | Green Advantages |
|---|---|---|---|
| Immediate Releas Tablets | MCC, Starch, CMC | Binding, disintegration, filling | Renewable, safe, cost-effective |
| Sustained Releas Tablets | HPMC, Alginate Pectin | Matrix formation, releas control | Biodegradable, non-toxic |
| Capsules | Gelatin, HPMC | Encapsulation, dissolution | Natural, patient-friendly |
| Topical Gels | Chitosan, HA, Agar | Gelling, mucoadhesion | Bioactive, sustainable |
| Injectable Systems | HA, Collagen, Chitosa | Viscosity, biocompatibility | Biocompatible, degradable |

## 5. Advantages of Green Multifunctional Approaches

The adoption of natural polymer excipients in multifunctional applications provides substantial environmental benefits through reduced resource consumption, lower carbon emissions, and decreased waste generation. Consolidation of multiple functions within single renewable components eliminates the need for petroleum-based synthetic excipients, significantly reducing the environmental footprint of pharmaceutical manufacturing [28].

Life cycle assessments demonstrate that natural polymer-based formulations achieve 40-60% reduction in carbon emissions compared to synthetic excipient systems. The biodegradable nature prevents environmental accumulation while supporting circular economy principles through waste valorisation approaches. Green processing technologies including enzymatic modification and biotechnological production further enhance environmental benefits [29].

Multifunctional natural polymer excipients provide significant economic advantages through formulation simplification, reduced raw material costs, and streamlined manufacturing processes. The consolidation of multiple functions within fewer components reduces inventory requirements, quality control testing, and potential incompatibility issues. Manufacturing efficiency improvements include shorter processing times, reduced equipment cleaning, and simplified batch records [30].

Cost-effectiveness extends beyond raw material savings to include reduced regulatory burden through established safety profiles of natural excipients. The GRAS status and pharmacopeial recognition of many natural polymers facilitate faster approval processes while reducing development costs. Market advantages include consumer preference for natural ingredients and improved product positioning [31].

## 6. Specific Natural Polymers and Their Pharmaceutical Applications

### 6.1 Chitosan: The Versatile Polycationic Polymer

The pharmaceutical applications of specific natural polymers demonstrate their versatility and effectiveness across diverse drug delivery systems and dosage forms. Each natural polymer exhibits unique properties that make it suitable for particular applications while offering advantages over synthetic alternatives [32].

Chitosan, derived from chitin deacetylation, stands out as one of the most extensively studied natural polymers due to its unique cationic nature and multifunctional properties. Its positive charge at physiological enables strong electrostatic interactions with negatively charged biological surfaces, making it an excellent mucoadhesive agent for various drug delivery applications [33].

The antimicrobial properties of chitosan provide additional therapeutic benefits in wound healing formulations and antimicrobial drug delivery systems. Recent studies have demonstrated chitosan's effectiveness in enhancing drug permeation across biological membranes through tight junction modulation, making it valuable for transmucosal delivery applications. However, challenges including pH-dependent solubility and batch-to-batch variability require careful formulation consideration and quality control measures [34].

### 6.2 Gelatin: The Gold Standard Protein Polymer

Gelatin remains the most widely used protein-based pharmaceutical excipient, with applications ranging from hard and soft capsule shells to hydrogel drug carriers. Its thermos reversible gelation properties enable temperature-controlled processing and drug release, while its excellent film-forming characteristics make it ideal for coating applications [35].

The biocompatibility and biodegradability of gelatin are well-established through decades of pharmaceutical use, providing regulatory confidence and patient acceptance. Recent innovations in gelatin modification, including crosslinking and chemical derivatization, have expanded its applications to sustained release systems and tissue engineering scaffolds [36].

### 6.3 Plant Gums: Nature's Rheology Modifiers

Plant gums, including guar gum and xanthan gum, serve as natural rheology modifiers with applications spanning from simple thickening to complex controlled release systems [37].

Xanthan gum's pseudoplastic behaviour stability over wide pH and temperature ranges makes it particularly valuable for liquid formulations [38].

The synergistic interactions between different plant gums enable the development of optimized formulations with tailored properties. For example, the combination of xanthan and guar gum produces enhanced viscosity and improved gel strength compared to individual components [39].

## 7. Challenges and Quality Control Considerations

Natural polymer excipients present unique quality control challenges related to inherent variability from biological sources and seasonal variations. Batch-to-batch consistency requires comprehensive analytical characterization and specification development that accounts for acceptable variability ranges while ensuring pharmaceutical performance. Advanced analytical methods including molecular weight distribution analysis, functional group quantification, and rheological testing enable detailed quality assessment [40].

Standardization efforts focus on developing performance-based specifications that evaluate functional properties rather than purely compositional parameters. This approach ensures that natural variability does not compromise pharmaceutical performance while maintaining the benefits of renewable resource utilization. Supplier qualification programs and ongoing monitoring ensure consistent supply of materials meeting pharmaceutical requirements [41].

Manufacturing with multifunctional natural polymer excipients requires careful optimization of processing parameters to maintain multiple functional properties simultaneously [42].

Traditional processing approaches focusing on single properties may not adequately address the complex requirements of multifunctional systems. Equipment selection and process design must accommodate the unique characteristics of natural polymers while ensuring consistent performance [43]. Scale-up considerations for multifunctional systems require validation of all functional aspects during scaling operations. The interconnected nature of properties in multifunctional systems necessitates comprehensive process validation and control strategies. Quality by Design approaches enable systematic optimization of processing conditions while maintaining green manufacturing principles [44].

## 8. Recent Advances and Technological Innovations

Recent developments in green synthesis technologies have revolutionized natural polymer modification while maintaining environmental benefits [45].

Enzymatic modification techniques provide selective functionalization under mild conditions, enhancing multifunctional properties without compromising biodegradability. Supercritical fluid technology enables solvent-free modification, eliminating environmental concerns while producing high-purity modified polymers [46,47].

Biotechnological approaches including microbial fermentation and enzymatic processing offer sustainable production methods for complex natural polymer excipients. These technologies enable precise control over polymer properties while operating under environmentally benign conditions. The integration of artificial intelligence and machine learning accelerates the identification and optimization of green synthesis pathways [47].

Nanotechnology integration with natural polymer excipients creates sophisticated multifunctional systems with enhanced properties while maintaining environmental sustainability. Natural polymer nanoparticles demonstrate improved bioavailability, targeted delivery, and controlled release characteristics. Surface modification with biocompatible ligands enables active targeting while preserving green chemistry principles [48].

Hybrid systems combining natural polymers with synthetic components in optimized ratios achieve enhanced performance while maintaining biodegradability. These systems leverage the multifunctional capabilities of natural polymers while addressing limitations through minimal synthetic component integration. Maintaining natural polymer content above 50% preserves biodegradability while achieving improved mechanical properties [49].

## 9. Future Perspectives

Future applications of green multifunctional natural polymer excipients will focus on personalized medicine platforms that adapt to individual patient requirements while maintaining environmental sustainability. 3D printing technologies utilizing natural polymers enable creation of personalized dosage forms with complex geometries and tailored release profiles. The biocompatible nature of natural polymers supports patient-specific therapeutic approaches [50].

Bio responsive systems utilizing natural polymers will monitor physiological conditions and adjust drug delivery accordingly while maintaining multifunctional benefits. Integration of sensing capabilities with therapeutic functions represents advanced multifunctional design approaches. These systems enable precision medicine while supporting sustainable pharmaceutical manufacturing [51].

Regulatory frameworks are evolving to support innovative multifunctional excipient systems while ensuring safety and environmental responsibility. Performance-based specifications and risk-based evaluation approaches facilitate innovation in green excipient development. International harmonization efforts aim to establish consistent standards for natural polymer excipients across regulatory jurisdictions [52]. Future regulatory developments will likely emphasize environmental impact assessment and sustainability metrics in excipient evaluation. The integration of green chemistry principles into regulatory guidelines supports the adoption of environmentally responsible excipient systems. These developments create favourable conditions for continued innovation in green multifunctional natural polymer excipients [53].

## 10. Conclusion

Natural polymer excipients represent a transformative approach to pharmaceutical formulation that aligns sustainability with functionality, offering multifaceted solutions to contemporary drug delivery challenges. This comprehensive review has demonstrated that natural polymers derived from plant, animal, microbial, and marine sources provide exceptional versatility as pharmaceutical excipients while adhering to green chemistry principles [54].

The multifunctional nature of natural polymers enables them to serve simultaneously as binding agents, disintegrants, film formers, matrix formers, and controlled release modifiers, potentially simplifying formulations and reducing the number of required excipients. Key natural polymers including chitosan, gelatin, HPMC, xanthan gum, pectin, and alginate have demonstrated superior performance in various pharmaceutical applications while offering inherent advantages of biodegradability, biocompatibility, and sustainable sourcing [55].

The green chemistry benefits of natural polymers are particularly significant in the current era of environmental consciousness and regulatory emphasis on sustainability. These biopolymers offer 60-80% reduction in carbon footprint, complete biodegradability within 6-12 months, and elimination of persistent environmental contaminants compared to synthetic alternatives. The renewable nature of their sources provides long-term supply security while supporting agricultural economies and reducing dependence on finite petroleum resources [56].

**References**


1. Mounika C, Vudikala P. Ecofriendly Excipients for Sustainable Pharmaceutical Development. Journal of Pharma Insights and Research. 2025 Feb 5;3(1):261-8.
2. Saha T, Masum ZU, Mondal SK, Hossain MS, Jobaer MA, Shahin RI, Fahad T. Application of natural polymers as pharmaceutical excipients. Global J Life Sci Biol Res. 2018;4(1)15.
3. Vegad U, Patel M, Khunt D, Zupančič O, Chauhan S, Paudel A. pH stimuli-responsive hydrogels from non-cellulosic biopolymers for drug delivery. Frontiers in Bioengineering and Biotechnology. 2023 Sep 12; 11:1270364.
4. Dave VS, Saoji SD, Raut NA, Haware RV. Excipient variability and its impact on dosage form functionality. Journal of pharmaceutical sciences. 2015 Mar 1;104(3):906-15.
5. Zain M, Arbaz S, Adnan S, Deshmukh R. Applications of Natural Polymers as Pharmaceutical Excipients in Solid Oral Dosage Forms. International Journal of Research in Pharmacy and Allied Science. 2024 Nov 8;3(5):26-33.
6. Patel RN, Keriwala TM, Upasani VV, Gujarathi P, Suryawanshi M, Vinchurkar K. Natural Excipients in Solid Dosage Forms. InInnovative Pharmaceutical Excipients: Natural Sources 2025 Jul 29, 229-248.
7. Carsanba E, Zhang F, Wang X. Fermentation Strategies for Production of Pharmaceutical Terpenoids by Recombinant Yeast: A Review. Biotechnology Reports. 2021 Mar, 29-38.
8. Frosi I, Balduzzi A, Moretto G, Colombo R, Papetti A. Towards valorization of food-waste-derived pectin: recent advances on their characterization and application. Molecules. 2023 Sep 1;28(17):6390.
9. Riseh RS, Vazvani MG, Hassanisaadi M, Thakur VK. Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. Industrial Crops and Products. 2024 Feb 1; 208:117904.
10. Rajeswari AVS, Satyanarayana SV, Rao VG, Anusha H, Raju KV. An Overview on Natural Polymers as Excipients in Pharmaceutical Dosage Forms. Asian Journal of Pharmaceutical Analysis and Medicinal Chemistry. 2021;9(1):37-43.
11. Kumar MNVR. Natural Polymers: Classification, Processing and Applications. In: Natural Polymers: Structure, Properties, and Applications. Elsevier; 2024, 23-47
12. Seema M, Chandra P, Neelkant P, Hina C, Minakshi S, Tajdar SA. A Review on Natural Plant Based Polymers: A Brilliant Pharmaceutical Excipients. Int J Food Nutr Sci. 2022;11(7).
13. Rinaudo M. Chitin and chitosan: Properties and applications. Progress in polymer science. 2006 Jul 1;31(7):603-32.
14. Siddiqui SA, Erol Z, Rugji J, Taşçı F, Kahraman HA, Toppi V, Musa L, Di Giacinto G, Bahmid NA, Mehdizadeh M, Castro-Muñoz R. An overview of fermentation in the food industry-looking back from a new perspective. Bioresources and bioprocessing. 2023 Nov 28;10(1):85.
15. Muanprasat C, Chatsudthipong V. Algal Phycocolloids: Bioactivities and Pharmaceutical Applications. Marine Drugs. 2023 Jun 27;21(7):328.
16. Anastas P, Eghbali N. Green chemistry: principles and practice. Chemical society reviews. 2010;39(1):301-12.
17. Belkhir L, Elmeligi A. Carbon footprint of the global pharmaceutical industry and relative impact of its major players. Journal of Cleaner Production. 2019 Mar 20; 214:185-94.
18. Zain M, Arbaz S, Adnan S, Deshmukh R. Applications of Natural Polymers as Pharmaceutical Excipients in Solid Oral Dosage Forms. International Journal of Research in Pharmacy and Allied Science. 2024 Nov 8;3(5):26-33.
19. Telrandhe MU. Coprocessed Excipients: Multifunctional Excipients for Solid Oral, Liquid, Semisolid, Parenteral, and Biological Preparations. Asian Journal of Pharmaceutics (AJP). 2023 Dec 15;17(04).

20. Sharma N, Yadav N. Natural Polymers as Pharmaceutical Excipients: Applications and Advances. World J Pharm Res. 2024;13(8):1120-1133.
21. Jacob S, Kather FS, Boddu SH, Attimarad M, Nair AB. Nanosuspension innovations: expanding horizons in drug delivery techniques. Pharmaceutics. 2025 Jan 19;17(1):136.
22. Karolewicz B. A review of polymers as multifunctional excipients in drug dosage form technology. Saudi Pharmaceutical Journal. 2016 Sep 1;24(5):525-36.
23. Rowe RC, Sheskey PJ, Quinn ME. Microcrystalline Cellulose. In: Handbook of Pharmaceutical Excipients. 7th ed. London: Pharmaceutical Press; 2020, 350-354.
24. Vlad RA, Pintea A, Pintea C, Rédai EM, Antonoaea P, Bîrsan M, Ciurba A. Hydroxypropyl Methylcellulose-A Key Excipient in Pharmaceutical Drug Delivery Systems. Pharmaceutics. 2025 Jun 16;17(6):784.
25. Mounika C, Vudikala P. Ecofriendly Excipients for Sustainable Pharmaceutical Development. Journal of Pharma Insights and Research. 2025 Feb 5;3(1):261-268.
26. Jadav M, Pooja D, Adams DJ, Kulhari H. Advances in xanthan gum-based systems for the delivery of therapeutic agents. Pharmaceutics. 2023 Jan 25;15(2):402.
27. Karava A, Lazaridou M, Nanaki S, Michailidou G, Christodoulou E, Kostoglou M, Iatrou H, Bikiaris DN. Chitosan derivatives with mucoadhesive and antimicrobial properties for simultaneous nanoencapsulation and extended ocular release formulations of dexamethasone and chloramphenicol drugs. Pharmaceutics. 2020 Jun 26;12(6):594.
28. Patel RN, et al. Natural Polymers as Pharmaceutical Excipients: A Sustainable Approach for Drug Delivery Systems. In: Jailani S, Vinchurkar K, Suryawanshi M, Mane S, editors. Innovative Pharmaceutical Excipients: Natural Sources. Singapore: Springer; 2025,185-210.
29. Ramesh P, Vinodh S. State of art review on Life Cycle Assessment of polymers. International Journal of Sustainable Engineering. 2020 Nov 1;13(6):411-22.
30. Bhardwaj H, Khute S, Sahu RK, Jangde RK. Recent Advances in Water-Soluble Polymer and Polymeric Nanoparticles for Pharmaceutical Application. Current Nanoscience. 2025 Jul;21(4):565-84.
31. Ruiz-Picazo A, Lozoya-Agullo I, González-Álvarez I, Bermejo M, González-Álvarez M. Effect of excipients on oral absorption process according to the different gastrointestinal segments. Expert Opinion on Drug Delivery. 2021 Aug 3;18(8):1005-24.
32. Li J, Mooney DJ. Designing hydrogels for controlled drug delivery. Nature Reviews Materials. 2016 Oct 18;1(12):1-7.
33. Shariatinia Z. Pharmaceutical applications of chitosan. Advances in colloid and interface science. 2019 Jan 1; 263:131-94.
34. Dai T, Tanaka M, Huang YY, Hamblin MR. Chitosan preparations for wounds and burns: antimicrobial and wound-healing effects. Expert review of anti-infective therapy. 2011 Jul 1;9(7):857-79.
35. Schrieber R, Gareis H. Gelatine handbook: theory and industrial practice. John Wiley & Sons; 2007 Apr 20.
36. Nikkhah M, Akbari M, Paul A, Memic A, Dolatshahi-Pirouz A, Khademhosseini A. Gelatin-based biomaterials for tissue engineering and stem cell bioengineering. Biomaterials from nature for advanced devices and therapies. 2016 Oct 14:37-62.
37. Shiam MA, Islam MS, Ahmad I, Haque SS. A review of plant-derived gums and mucilages: Structural chemistry, film forming properties and application. Journal of Plastic Film & Sheeting. 2025 Apr;41(2):195-237.
38. Varma K, Gopi S. Biopolymers and their role in medicinal and pharmaceutical applications. In Biopolymers and their industrial applications 2021 Jan 1, 175-191.
39. Ahmed J, Eqbal MD. Rheological properties of high-pressure treated xanthan gum and guar gum blend solutions: a response surface approach. Journal of Food Process Engineering. 2023 Dec;46(12): e14449.
40. Dave VS, Saoji SD, Raut NA, Haware RV. Excipient variability and its impact on dosage form functionality. Journal of pharmaceutical sciences. 2015 Mar 1;104(3):906-15.

41. International Pharmaceutical Excipients Council (IPEC). Qualification of Excipients for Pharmaceutical Use. IPEC Guide. 2008.
42. Singh P, Mishra G, Dinda SC. Natural excipients in pharmaceutical formulations. In Evidence based validation of traditional medicines: a comprehensive approach 2021 Jan 19,829-869.
43. Flórez M, Cazón P, Vázquez M. Selected biopolymers' processing and their applications: A review. Polymers. 2023 Jan 26;15(3):641.
44. Yeom SB, Choi DH. Scale-up strategy in quality by design approach for pharmaceutical blending process with discrete element method simulation. Pharmaceutics. 2019 Jun 6;11(6):264.
45. Azevedo HS, Santos TC, Reis RL. Controlling the degradation of natural polymers for biomedical applications. InNatural-based polymers for biomedical applications 2008 Jan 1, 106-128.
46. Delplace V, Nicolas J. Degradable vinyl polymers for biomedical applications. Nature chemistry. 2015 Oct;7(10):771-84.
47. Ulery BD, Nair LS, Laurencin CT. Biomedical applications of biodegradable polymers. Journal of polymer science Part B: polymer physics. 2011 Jun 15;49(12):832-64.
48. Ravichandran R, Sundarrajan S, Venugopal JR, Mukherjee S, Ramakrishna S. Advances in polymeric systems for tissue engineering and biomedical applications. Macromolecular bioscience. 2012 Mar;12(3):286-311.
49. Idrees H, Zaidi SZ, Sabir A, Khan RU, Zhang X, Hassan SU. A review of biodegradable natural polymer-based nanoparticles for drug delivery applications. Nanomaterials. 2020 Oct 5;10(10):1970.
50. Trenfield SJ, Awad A, Goyanes A, Gaisford S, Basit AW. 3D printing pharmaceuticals: drug development to frontline care. Trends in pharmacological sciences. 2018 May 1;39(5):440-451.
51. Mastnak T, Maver U, Finšgar M. Addressing the needs of the rapidly aging society through the development of multifunctional bioactive coatings for orthopedic applications. International journal of molecular sciences. 2022 Mar 3;23(5):2786.
52. Elder DP, Kuentz M, Holm R. Pharmaceutical excipients—quality, regulatory and biopharmaceutical considerations. European journal of pharmaceutical sciences. 2016 May 25; 87:88-99.
53. Saito J, Agrawal A, Patravale V, Pandya A, Orubu S, Zhao M, Andrews GP, Petit-Turcotte C, Landry H, Croker A, Nakamura H. The current states, challenges, ongoing efforts, and future perspectives of pharmaceutical excipients in pediatric patients in each country and region. Children. 2022 Mar 23;9(4):453.
54. Ogaji IJ, Nep EI, Audu-Peter JD. Advances in natural polymers as pharmaceutical excipients. Pharmaceutica Analytica Acta. 2012 Jan 18;3(1):1-6.
55. Silva AC, Silvestre AJ, Vilela C, Freire CS. Natural polymers-based materials: A contribution to a greener future. Molecules. 2021 Dec 24;27(1):94.
56. Kar S, Sanderson H, Roy K, Benfenati E, Leszczynski J. Green chemistry in the synthesis of pharmaceuticals. Chemical Reviews. 2021 Dec 15;122(3):3637-710.