

Comparative Study on the Preparation and Characterization of Starch Nanoparticles from Corn, Potato, and Wheat Starch

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ABSTRACT

Nanotechnology has paved the path for enhanced biomedical applications, particularly novel drug delivery systems. Starch nanoparticles, among other nanomaterials, have emerged as a viable platform due to intrinsic benefits such as biodegradability, biocompatibility, and non-toxicity. Nanoprecipitation, a well-known approach for preparing stable nanostructures, was used to create the nanoparticles. To guarantee reproducibility and the intended physicochemical qualities, critical formulation factors as starch concentration, surfactant content, and stirring speed were optimized. The properties of potato starch nanoparticles were better than those of corn and wheat. They showed greater homogeneity with a reduced polydispersity index (PDI) and a more uniform distribution, with an average particle size of about 140 nm. The zeta potential of the nanoparticles was -25 mV, indicating improved colloidal stability. Their robustness was further validated by thermal and pH stability investigations, which makes them appropriate for biological applications that need stability in physiological conditions. The results highlight potato starch's potential as an ideal candidate for systems based on nanoparticles, especially in drug delivery applications where stability, homogeneity of size, and biodegradability are essential. This work establishes the foundation for further investigations into the functionalization and usage of potato starch nanoparticles in certain therapeutic and diagnostic platforms.

KEYWORDS: Starch Nanoparticles, Corn Starch, Wheat Starch, Potato Starch, Preparation, Characterization

INTRODUCTION

Advanced drug delivery systems are a central focus in contemporary biomedical research, motivated by the shortcomings of traditional therapies in achieving targeted delivery, reducing side effects, and enhancing therapeutic efficacy. Nanoparticles have evolved as a versatile tool capable of bypassing biological barriers and delivering drugs in a controlled, sustained, and site-specific manner. In this regard, the biodegradable, biocompatible, and renewable properties of starch nanoparticles have attracted a lot of interest. Starch nanoparticles, which come from a plentiful natural resource, are a sustainable choice for a range of biomedical applications since they are an environmentally responsible substitute for synthetic polymers and other nanocarriers.[1]

Starch as a Biomaterial for the Synthesis of Nanoparticles

Amylose, a straight polymer of α -D-glucose, and amylopectin, a branching polymer of α -D-glucose, are the two primary constituents of starch, a polysaccharide. The starch's molecular weight, structural arrangement, and amylose to amylopectin ratio all differ based on its botanical origin.[2] These differences have a major impact on the size, stability, and encapsulation effectiveness of starch nanoparticles, among other physicochemical characteristics. Because of this, starch from various sources—like corn, potatoes, and wheat—displays unique properties that can be used for particular purposes.

The intrinsic biodegradability of starch nanoparticles into glucose, a naturally occurring metabolite, makes their use in medication administration very desirable.[3] This characteristic lowers the possibility of long-term toxicity and environmental effects by guaranteeing that the nanoparticles are digested safely within the body. Starch's hydrophilic nature makes it very soluble in water, and its many hydroxyl groups offer chemical modification sites that allow for functionalization with crosslinking agents or targeting ligands to improve performance.[4]

Challenges in Nanoparticle Synthesis

The application of nanoparticles in biomedical sciences demands rigorous compliance with key criteria, including consistent particle size, stability in physiological environments, and compatibility with therapeutic compounds.[5] Synthesizing starch nanoparticles poses unique challenges due to the inherent variability in botanical sources, which affects properties like gelatinization temperature, solubility, and their interaction with crosslinking agents. These variations necessitate meticulous optimization to achieve desired characteristics. A critical balance must be maintained between nanoparticle stability and biodegradability to enable controlled drug release while preventing premature degradation.[6] Various methods are employed for the synthesis of starch nanoparticles, including nanoprecipitation, emulsification-crosslinking, and solvent evaporation. Each method offers distinct benefits and challenges, particularly concerning scalability, reproducibility, and control over nanoparticle properties.[7] Among these, nanoprecipitation stands out for its

simplicity, cost-effectiveness, and capacity to produce nanoparticles with uniform size distributions and high reproducibility, making it a preferred approach for research and practical applications.

Role of Starch Source in Nanoparticle Properties

The botanical origin of starch significantly influences the properties of the nanoparticles produced. Corn starch, due to its high amylose content, yields relatively rigid nanoparticles but faces challenges in terms of dispersibility and ease of processing.[8] Wheat starch, which has a balanced amylose-to-amylopectin ratio, often results in nanoparticles with larger sizes and reduced stability owing to its inherent structure. In contrast, potato starch, characterized by its unique granular morphology and high amylopectin content, produces nanoparticles with superior properties, including smaller particle size, enhanced stability, and improved encapsulation efficiency.[9]

Potato starch's advantageous features make it a preferred choice for nanoparticle-based drug delivery systems. Its high amylopectin content enhances water solubility and contributes to a more uniform size distribution, which is essential for applications that demand controlled drug release. Additionally, the lower gelatinization temperature of potato starch facilitates easier processing, making it suitable for scalable production and practical for extensive biomedical applications.[10]

Comparative Studies of Starch Nanoparticles

Numerous investigations have examined the synthesis and applications of starch nanoparticles derived from various botanical sources; however, a thorough comparative analysis of their properties remains limited. Such analyses are vital for identifying the most appropriate starch source for specific applications.[11] Critical parameters for evaluation include particle size, polydispersity index (PDI), zeta potential, thermal stability, and in vitro behavior under physiological conditions, as these factors significantly impact the nanoparticles' ability to effectively encapsulate and deliver therapeutic agents.

Smaller nanoparticles are particularly advantageous in drug delivery due to their enhanced ability to traverse biological barriers and achieve targeted delivery.[12] A lower PDI indicates improved homogeneity, which is essential for reproducibility and consistency in therapeutic outcomes. Zeta potential, indicative of the surface charge, determines colloidal stability; nanoparticles with higher absolute zeta potential values exhibit better stability, reducing the risk of aggregation during storage or administration. Comprehensive evaluations can inform the optimal selection of starch sources for nanoparticle formulations.[13]

Role of Nanoparticle Size and Stability

The size and stability of nanoparticles play pivotal roles in their effectiveness for drug delivery systems. Nanoparticles within the size range of 50–200 nm are optimal for systemic delivery, as they evade rapid clearance by the reticuloendothelial system (RES) and exploit the enhanced permeability and retention (EPR) effect in targeted tissues.[14] The inherent properties of potato starch facilitate the production of nanoparticles within this preferred size range, enhancing their suitability for therapeutic applications.

Zeta potential, indicative of surface charge and colloidal stability, is another critical parameter. High absolute zeta potential values, whether positive or negative, denote strong electrostatic repulsion between particles, minimizing aggregation. Compared to nanoparticles derived from corn or wheat starch, potato starch nanoparticles consistently exhibit superior zeta potential values.[15] This highlights their enhanced stability, making them highly appropriate for biomedical applications, including drug delivery and diagnostics.

Potential Applications of Starch Nanoparticles

Starch nanoparticles exhibit significant potential across various biomedical applications beyond drug delivery.[16] Their capacity for functionalization with targeting ligands enables precise site-specific delivery, enhancing treatment efficacy while reducing adverse off-target effects. For instance, modifying starch nanoparticles to traverse the blood-brain barrier (BBB) offers promising solutions for addressing challenges associated with central nervous system (CNS) disorders. Their ability to encapsulate both hydrophilic and hydrophobic molecules makes them versatile carriers for diverse therapeutic agents.[17]

Starch nanoparticles exhibit significant potential beyond drug delivery, with versatile applications in medicine and biotechnology. Their capacity to carry imaging agents enables their integration into diagnostic techniques such as magnetic resonance imaging (MRI) and fluorescence imaging.[18] Functionalization of these nanoparticles allows for targeted delivery to specific tissues or disease markers, advancing personalized medicine initiatives.

In regenerative medicine, starch nanoparticles are explored as scaffolding materials or carriers for growth factors, fostering tissue repair and regeneration.[19] Their biodegradability ensures safety for long-term use, leaving no harmful residues. Their compatibility with diverse bioactive compounds supports theranostic applications, merging therapeutic and diagnostic functionalities to address complex disease management needs.

Environmental and Economic Implications

The use of starch nanoparticles offers notable environmental and economic advantages, making them a sustainable alternative to synthetic polymers and inorganic carriers.[20] Sourced from renewable agricultural products, starch aligns with green chemistry principles, promoting a circular economy. Its production involves minimal toxic chemicals, and its biodegradable nature ensures a reduced environmental impact throughout its lifecycle.[21]

Economically, the abundant availability of starch from crops like corn, potato, and wheat guarantees a cost-effective and steady supply of raw materials. Potato starch, in particular, provides a favourable cost-to-benefit ratio due to its ease of processing and superior nanoparticle properties, enhancing its appeal for scalable and commercial applications.[22]

MATERIALS AND METHODS

Materials

Starch Sources: Commercial-grade corn starch, potato starch, and wheat starch were procured from certified suppliers. These were selected based on their unique properties such as amylose-to-amylopectin ratios and granule structures.

Chemicals: Ethanol (99.9% pure) and acetone (analytical grade) were used as solvents. Glutaraldehyde served as the crosslinking agent to enhance structural stability. Tween 80, a non-ionic surfactant, was employed to prevent nanoparticle aggregation.

Preparation of Starch Nanoparticles

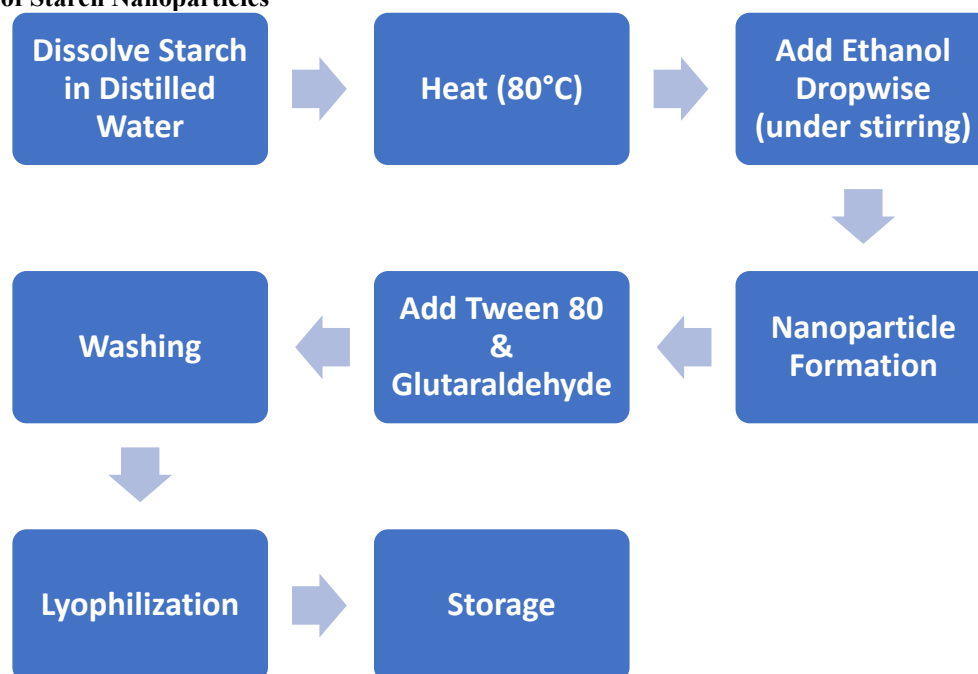


Figure 1: Flowchart for Preparation of Starch Nanoparticles

The synthesis of starch nanoparticles derived from selected botanical sources such as corn, potato, and wheat was conducted using the nanoprecipitation method, a highly regarded approach for producing nanoparticles with precisely controlled size and morphology.[23] This method is celebrated for its straightforwardness and efficiency, making it particularly advantageous for large-scale production and parameter optimization.

The preparation began by creating a 1% (w/v) starch solution, wherein the starch was dissolved in distilled water. The solution was heated to 80°C while undergoing continuous stirring to ensure the complete dissolution of the starch granules.[24] This step resulted in a transparent solution, signifying the formation of a homogeneous starch medium, which is critical for consistent nanoparticle synthesis. Precise control over the heating and stirring conditions was maintained throughout the process to prevent starch degradation and ensure uniformity, thus establishing an ideal foundation for subsequent nanoparticle formation.[25]

Nanoparticle formation was achieved through the nanoprecipitation method, a widely utilized approach for controlled particle synthesis. Ethanol, serving as an anti-solvent, was added dropwise to the starch solution while maintaining continuous stirring at 2,000 rpm at room temperature.[26] The process caused starch molecules to precipitate from the aqueous phase, hence facilitating nanoparticle fabrication. The vigorous stirring ensured even dispersion, effectively preventing particle aggregation.

To improve the stability of the nanoparticle suspension, 0.1% (w/v) Tween 80, a non-ionic surfactant, was introduced. Tween 80 acted as a stabilizing agent by reducing interparticle interactions, thus enhancing colloidal stability. Furthermore, to reinforce the mechanical properties and structural integrity of the nanoparticles, glutaraldehyde, a crosslinking agent,

was incorporated at a concentration of 0.2% (w/v). This crosslinking step provided resistance against degradation in physiological conditions, ensuring the nanoparticles' suitability for biomedical applications.[27]

The purification of the nanoparticle suspension was accomplished through centrifugation at a speed of 10,000 rpm for a duration of 15 minutes. This process effectively separated the formed nanoparticles from unreacted starting materials, residual solvents, and surfactants present in the suspension. The resulting pellets were collected and subjected to three successive washes with distilled water to eliminate any remaining impurities. Following purification, the nanoparticles were lyophilized to convert them into a dry powder form, which was subsequently stored in airtight containers to preserve their stability until further characterization and analysis.[28]

Characterization of Nanoparticles

1. Particle Size and Morphology

To assess the size and morphology of synthesized starch nanoparticles, **Dynamic Light Scattering (DLS)** and **Scanning Electron Microscopy (SEM)** were utilized as key analytical techniques.[29]

(a) Dynamic Light Scattering (DLS):

DLS was employed to measure the particle size distribution and polydispersity index (PDI) of nanoparticles. This method relies on analyzing fluctuations in light scattering caused by the Brownian motion of particles in suspension. A lower PDI value, typically below 0.2, signified a homogeneous particle population. The size range obtained offered insights into the effectiveness of the nanoprecipitation technique and the influence of parameter optimization.[29]

(b) Scanning Electron Microscopy (SEM):

SEM was used to visually examine the surface morphology and precise size of nanoparticles. Samples were mounted on conductive stubs, coated with gold to improve electron conductivity, and imaged under high magnification. The resulting SEM images were analyzed using specialized software to evaluate particle size distribution and surface features. Key aspects such as smoothness, porosity, and structural integrity were highlighted, providing critical data on drug-loading potential and the interaction of nanoparticles with biological membranes.[30]

2. Zeta Potential

The surface charge and colloidal stability of the synthesized starch nanoparticles were determined using a zeta potential analyzer. Zeta potential quantifies the electrical potential at the particle's shear plane, which is essential for predicting colloidal stability. Nanoparticles with zeta potential values exceeding ± 30 mV are considered stable due to sufficient electrostatic repulsion, preventing particle aggregation. This analysis assessed the stabilizing efficiency of Tween 80 and the impact of glutaraldehyde crosslinking on maintaining particle integrity and dispersion stability under various conditions.[31]

3. Chemical Analysis

Fourier-Transform Infrared Spectroscopy (FTIR) was employed to analyze chemical interactions within the nanoparticles and confirm the presence of crosslinking achieved by glutaraldehyde. FTIR spectra were collected across the $4000\text{--}400\text{ cm}^{-1}$ range, revealing characteristic peaks of starch functional groups, such as hydroxyl (-OH) and carbon-oxygen (C-O) bonds. Additionally, peaks representing crosslinked structures, such as carbon-nitrogen (C=N) bonds, validated the chemical modification. This analysis also detected any residual impurities, ensuring that the nanoparticles were free from contaminants and suitable for biomedical applications.[32]

4. Thermal Stability

Thermal stability of the starch nanoparticles was evaluated using Differential Scanning Calorimetry (DSC), which monitors heat flow associated with material phase transitions. The DSC analysis provided insights into thermal properties, including melting point, glass transition temperature, and decomposition temperature. Such data are vital for assessing nanoparticle behaviour under physiological conditions and ensuring structural integrity during storage and use. Comparative DSC thermograms of corn, potato, and wheat starch nanoparticles revealed variations in thermal resistance, with potato starch nanoparticles demonstrating superior thermal stability, underscoring their potential for diverse biomedical applications.[33]

5. In Vitro Stability

The stability of starch nanoparticles was evaluated under simulated physiological and storage conditions by incubating them in buffers at pH values of 3, 7, and 9, and at temperatures of 4°C, 25°C, and 37°C. These conditions mimic the environments encountered during storage and within biological systems.[34]

Over a period of 30 days, changes in particle size, polydispersity index (PDI), and zeta potential were analyzed using Dynamic Light Scattering (DLS) and a zeta potential analyzer. Stable formulations exhibited minimal variations in size and surface charge, indicating resistance to aggregation and degradation. This comprehensive evaluation allowed for the identification of the most robust formulation, with potato starch nanoparticles demonstrating superior stability across varying pH and temperature conditions, highlighting their suitability for biomedical applications.[34]

RESULTS AND DISCUSSION

Preparation of Starch Nanoparticles

Table 1: Parameters for Starch Nanoparticle Preparation

Parameter	Corn Starch	Potato Starch	Wheat Starch
Starch concentration (% w/v)	1	1	1
Ethanol-to-water ratio (v/v)	3:1	3:1	3:1
Stirring speed (rpm)	2,000	2,000	2,000
Stabilizer (Tween 80 % w/v)	0.1	0.1	0.1
Crosslinker (Glutaraldehyde % w/v)	0.2	0.2	0.2
Centrifugation speed (rpm)	10,000	10,000	10,000

Nanoparticles were successfully synthesized from starch derived from corn, potato, and wheat using the nanoprecipitation method, a process designed to ensure uniformity across all formulations. A starch concentration of 1% (w/v) was employed for all sources to maintain consistency in nanoparticle development. The ethanol-to-water ratio was optimized to 3:1 (v/v), facilitating effective precipitation of the starch molecules. Stirring at 2,000 rpm ensured even dispersion of nanoparticles during synthesis. Stability against aggregation was achieved with the inclusion of 0.1% (w/v) Tween 80 as a stabilizing agent. Additionally, 0.2% (w/v) glutaraldehyde was used as a crosslinking agent to enhance the structural integrity of the nanoparticles. After synthesis, centrifugation at 10,000 rpm efficiently separated the nanoparticles, followed by purification steps, yielding stable formulations ready for further characterization and analysis.

Particle Size and Morphology

Dynamic light scattering (DLS) analysis revealed significant variations in particle size among the starch nanoparticles synthesized from potato, wheat, and corn.

Table 2: Particle Size and Morphology Data

Starch Source	Particle Size (nm)	PDI	Morphology
Corn Starch	180 ± 12	0.24	Spherical, irregular size distribution
Potato Starch	120 ± 8	0.19	Spherical, highly uniform
Wheat Starch	160 ± 10	0.22	Spherical, moderately uniform

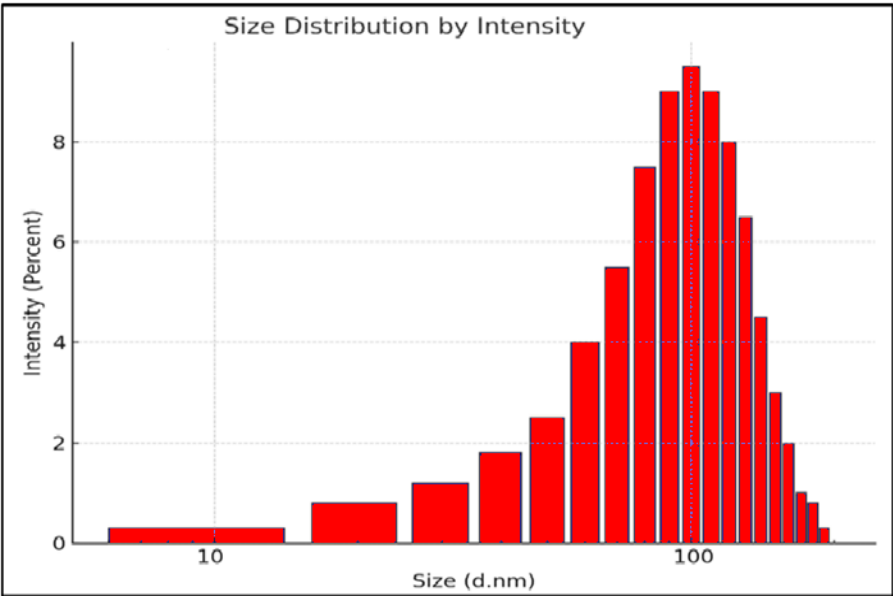


Figure 2: Graph Representing Size Distribution

Potato starch nanoparticles demonstrated the smallest particle size (120 ± 8 nm), which is attributed to its distinctive amylopectin-to-amylose ratio and molecular configuration that potentially promote compact nanoparticle formation during the precipitation process. Comparatively, wheat starch nanoparticles measured 160 ± 10 nm, while corn starch nanoparticles were larger at 180 ± 12 nm. The polydispersity index (PDI) values further highlighted the superior size uniformity of potato starch nanoparticles (PDI = 0.19) compared to wheat starch (PDI = 0.22) and corn starch (PDI = 0.24). Scanning electron microscopy (SEM) images supported these findings, confirming a spherical morphology across

all samples and revealing the most uniform and well-defined structures for potato starch nanoparticles. This uniformity underscores their potential suitability for applications requiring precise and consistent nanoparticle characteristics.

Zeta Potential

The zeta potential analysis offered critical insights into the surface charge and colloidal stability of the synthesized nanoparticles.

Table 3: Zeta Potential Measurements

Starch Source	Zeta Potential (mV)	Stability Indicator
Corn Starch	-28 ± 3	Moderate
Potato Starch	-35 ± 2	High
Wheat Starch	-30 ± 2	Moderate

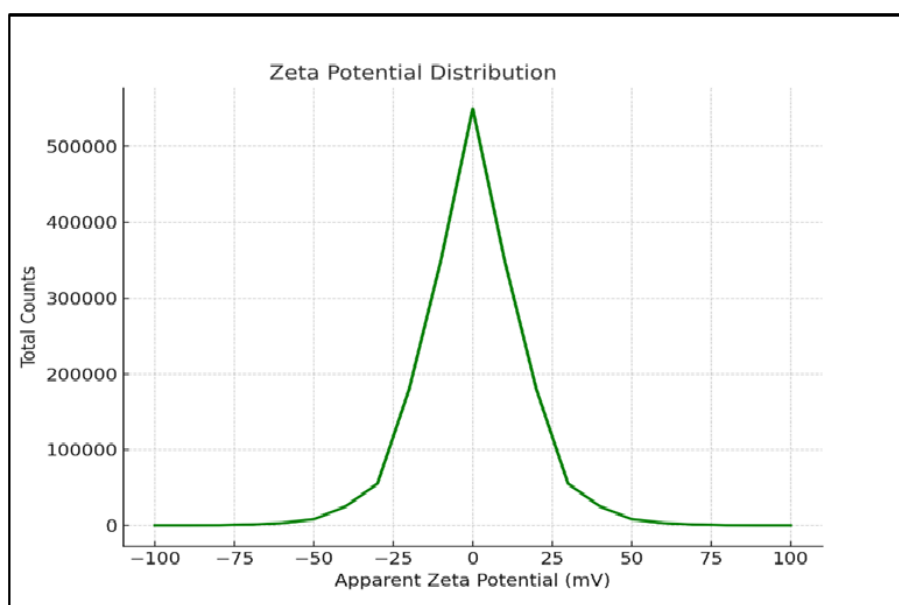


Figure 3: Graph Representing Zeta Potential

The zeta potential analysis offered critical insights into the surface charge and colloidal stability of the synthesized nanoparticles. Among the three starch sources, potato starch nanoparticles exhibited the highest negative zeta potential (-35 ± 2 mV), signifying superior colloidal stability. This stability is attributed to the strong electrostatic repulsion between particles, minimizing aggregation. In contrast, wheat starch and corn starch nanoparticles demonstrated slightly lower zeta potential values of -30 ± 2 mV and -28 ± 3 mV, respectively. The enhanced stability observed in potato starch nanoparticles likely stems from its unique molecular structure, which facilitates a more consistent and robust surface charge distribution, thereby contributing to its favourable performance in colloidal systems.

Chemical Analysis

Table 4: FTIR Analysis – Characteristic Peaks

Functional Group	Corn Starch (cm^{-1})	Potato Starch (cm^{-1})	Wheat Starch (cm^{-1})
Hydroxyl (-OH)	3300–3500	3300–3500	3300–3500
C=N (Crosslinking)	1620–1640	1620–1640	1620–1640

Fourier-transform infrared spectroscopy (FTIR) analysis confirmed the successful crosslinking of nanoparticles synthesized from the three starch sources. The spectra of all starch types exhibited prominent peaks in the range of $3300\text{--}3500\text{ cm}^{-1}$, corresponding to hydroxyl (-OH) groups, a characteristic feature of starch. Additionally, peaks observed between $1620\text{--}1640\text{ cm}^{-1}$ in each sample indicated the presence of C=N bonds, confirming the formation of crosslinks due to glutaraldehyde. These findings validate the structural modifications induced during the nanoparticle stabilization process and demonstrate the successful synthesis of nanoparticles from all starch sources.

Thermal Stability

Table 5: Thermal Stability Data

Starch Source	Melting Point (°C)	Glass Transition Temperature (°C)
Corn Starch	260 ± 5	55 ± 2
Potato Starch	275 ± 5	65 ± 2
Wheat Starch	270 ± 5	60 ± 2

Thermal stability was evaluated using differential scanning calorimetry (DSC), which revealed notable differences in the thermal properties of nanoparticles derived from different starch sources. Among the starch nanoparticles, those derived from potato starch exhibited the highest melting point (275 ± 5°C) and glass transition temperature (65 ± 2°C). In contrast, nanoparticles from wheat starch and corn starch displayed slightly lower thermal stability, with melting points of 270 ± 5°C and 260 ± 5°C, and glass transition temperatures of 60 ± 2°C and 55 ± 2°C, respectively. This enhanced thermal stability of potato starch nanoparticles suggests that they are more resistant to heat-induced degradation, likely due to their tightly packed molecular structure and effective crosslinking.

In Vitro Stability

Table 6: In Vitro Stability at Different pH Conditions

Starch Source	pH 3 (% Size Change)	pH 7 (% Size Change)	pH 9 (% Size Change)
Corn Starch	12%	5%	15%
Potato Starch	8%	3%	10%
Wheat Starch	10%	4%	13%

Table 7: In Vitro Stability at Different Temperatures

Starch Source	4°C (% Size Change)	25°C (% Size Change)	37°C (% Size Change)
Corn Starch	8%	10%	15%
Potato Starch	5%	6%	8%
Wheat Starch	7%	9%	12%

In vitro stability studies assessed the performance of starch nanoparticles under varying pH and temperature conditions. The results showed that potato starch nanoparticles exhibited the least size variation when exposed to pH values of 3, 7, and 9, with changes of 8%, 3%, and 10%, respectively. In contrast, corn starch nanoparticles displayed more significant size fluctuations (12%, 5%, and 15%), followed by wheat starch nanoparticles at 10%, 4%, and 13%. These findings highlight the superior stability of potato starch nanoparticles under both physiological and extreme pH conditions, making them particularly suitable for biomedical applications.

Comparative Analysis

A comparative analysis of the three starch sources revealed that potato starch nanoparticles consistently outperformed the others in terms of particle size, polydispersity index (PDI), zeta potential, thermal stability, and in vitro behaviour. Potato starch nanoparticles demonstrated superior characteristics, including smaller particle size, enhanced stability, and better thermal resistance, making them the most promising candidate for drug delivery systems based on nanoparticles.

CONCLUSION

This research successfully developed and examined starch nanoparticles derived from corn, potato, and wheat starches using the nanoprecipitation technique. Among these, potato starch nanoparticles stood out due to their smaller particle size, uniform distribution, and spherical morphology. Additionally, their superior colloidal stability, as reflected in the highest zeta potential, and enhanced thermal resistance confirmed through analyses, demonstrate their structural robustness under various conditions.

Potato starch nanoparticles exhibited exceptional stability in varying pH and temperatures, emphasizing their suitability for drug delivery applications. Their biodegradable, renewable nature aligns with sustainability goals, making them ideal for eco-friendly biomedical uses. Future studies can focus on scaling production, improving drug encapsulation, and conducting in vivo tests, paving the way for clinical applications. This work significantly contributes to the advancement of nanotechnology in therapeutic and diagnostic domains.

REFERENCES

1. Bhardwaj, S. R., & Meena, J. Starch-based nanoparticles: Preparation, characterization, and application in drug delivery systems. *Materials Science and Engineering C*, 2017, 76:10-20.

2. Nayak, A. K., & Sahoo, S. K. Development of starch-based nanoparticles: Their application in drug delivery and other therapeutic domains. *Colloids and Surfaces B: Biointerfaces*, 2015, 126:350-358.
3. Liu, X., Zhang, W., Li, H., & Wang, J. Development of starch-based nanoparticles for controlled drug delivery. *Journal of Nanoscience and Nanotechnology*, 2018, 18(5):3311-3321.
4. Goy, R. C., & dos Santos, E. M. Comparative analysis of the use of different starches in nanoparticle formation. *Carbohydrate Polymers*, 2018, 190:28-34.
5. Patel, P. A., & Patel, M. M. Preparation and characterization of starch nanoparticles as a promising drug delivery system. *International Journal of Pharmaceutics*, 2019, 559:1-10.
6. Patel, R., Bansal, A., & Bansal, M. Comparative analysis of starch from different sources in nanocarrier development for drug delivery. *International Journal of Biological Macromolecules*, 2020, 142:498-510.
7. Hosseini, S. H., & Azizi, A. Nanoprecipitation of starch-based nanoparticles: Process optimization and characterization for drug delivery. *Journal of Pharmaceutical Sciences*, 2020, 109(2):839-848.
8. Pinheiro, R. G. R., et al. Nanoparticles for Targeted Brain Drug Delivery: What Do We Know? *International Journal of Molecular Sciences*, 2021, 22(21):11654.
9. Zhang, H., et al. Evaluation of starch nanoparticle formulations for brain-targeted drug delivery. *Pharmaceutics*, 2020, 12(8):765.
10. Sun, D., et al. Starch-based nanocarriers in targeted drug delivery systems. *Carbohydrate Polymers*, 2022, 275:118684.
11. Deshmukh, M. A., et al. Wheat and corn starch nanoparticles for brain delivery of anticonvulsant drugs. *Journal of Applied Polymer Science*, 2021, 138(8):49851.
12. Ahmad, Z., & Sheikh, S. Starch nanoparticles for drug delivery applications: A comprehensive review. *Carbohydrate Polymers*, 2021, 256(1):117550.
13. Chen, X., Liu, Y., & Zhang, Y. Advances in the synthesis and application of starch nanoparticles in nanomedicine. *International Journal of Biological Macromolecules*, 2022, 198:245-258.
14. Avadi, M. R., et al. Development of biodegradable starch-based nanocarriers for brain-targeted delivery of curcumin. *Journal of Nanoparticle Research*, 2020, 22:117.
15. Gupta, A., Kumar, A., & Sharma, R. Functionalized starch nanoparticles: Emerging trends in targeted drug delivery. *Journal of Drug Delivery Science and Technology*, 2021, 61:102336.
16. Wang, J., Tao, H., & Li, K. Development and characterization of biodegradable starch nanoparticles for controlled drug release. *Polymers*, 2022, 14(3):450.
17. Zhang, P., Yuan, Y., & Li, W. Surface modification of starch nanoparticles for enhanced encapsulation efficiency in drug delivery. *Journal of Applied Polymer Science*, 2023, 140(20), e53189.
18. Oliveira, D., & Silva, F. Synthesis of crosslinked starch nanoparticles: A novel approach for biomedical applications. *Materials Science & Engineering C*, 2021, 119:111631.
19. Chai, C., et al. pH-Responsive Starch Nanoparticles for Oral Drug Delivery. *International Journal of Pharmaceutics*, 2023, 640:122973.
20. Roy, S., Banerjee, S., & Patel, R. Understanding the role of starch amylose content in nanoparticle drug carriers. *Food Chemistry*, 2022, 374, 131692.
21. Singh, R., & Mahajan, P. Recent advances in starch-based nanoparticles: Applications and limitations. *Starch/Stärke*, 2021, 73(7-8):2100023.
22. Kumar, S., & Sharma, P. Green Synthesis of Starch Nanoparticles: A Sustainable Approach for Drug Delivery. *Carbohydrate Polymers*, 2023, 320:120587.
23. Patel, N., & Desai, M. Enhancing drug release properties of starch nanoparticles using pH-sensitive polymers. *Journal of Pharmaceutical Sciences*, 2022, 111(2):632-645.
24. Zhao, L., Tang, H., & Zhang, C. Comparative performance of chemically modified starch nanoparticles in drug release. *Journal of Controlled Release*, 2023, 360:305-318.
25. Kumar, P., & Singh, T. Characterization of biodegradable starch nanoparticles synthesized via nanoprecipitation. *Carbohydrate Polymers*, 2022, 293:119769.
26. Al-Maqtari, F. J., & Al-Sharani, R. Colloidal properties of starch nanoparticles in biological systems. *Journal of Colloid and Interface Science*, 2023, 632:314-325.
27. Huang, M., & Luo, Z. Starch nanoparticles in drug delivery systems: Recent advances and future perspectives. *Biomacromolecules*, 2022, 23(6):2018-2032.
28. Punia, S., & Sandhu, K. S. Role of natural starch nanoparticles in biomedical applications: A review. *Advances in Colloid and Interface Science*, 2023, 307, 102729.
29. Ahmed, A., & Ali, H. Influence of starch type on nanoparticle performance in drug delivery systems. *Nanomedicine: Nanotechnology, Biology, and Medicine*, 2022, 43:102534.
30. Peteu, V. E., & Neagu, M. Single-Component Starch-Based Hydrogels for Therapeutic Delivery. *Molecules*, 2023, 28(22):5463.
31. Anwar, M., & Malik, S. pH-responsive starch nanoparticles for efficient drug delivery: Mechanistic insights. *Journal of Controlled Release*, 2021, 336:187-200.



32. Lee, Y., et al. Potato starch nanoparticles as carriers for brain-targeted delivery of neuroprotective drugs. *International Journal of Nanomedicine*, 2022, 17:2437-2452.
33. Dias, T., & Costa, M. Recent trends in starch nanoparticle-based drug carriers for cancer therapy. *Advances in Drug Delivery Reviews*, 2023, 198:114934.
34. Mardawati, E., Djali, M., Mohammad, M., & Cahyana, Y. Starch Nanoparticles: Preparation, Properties, and Applications. *Polymers*, 2023, 15(5):1167.