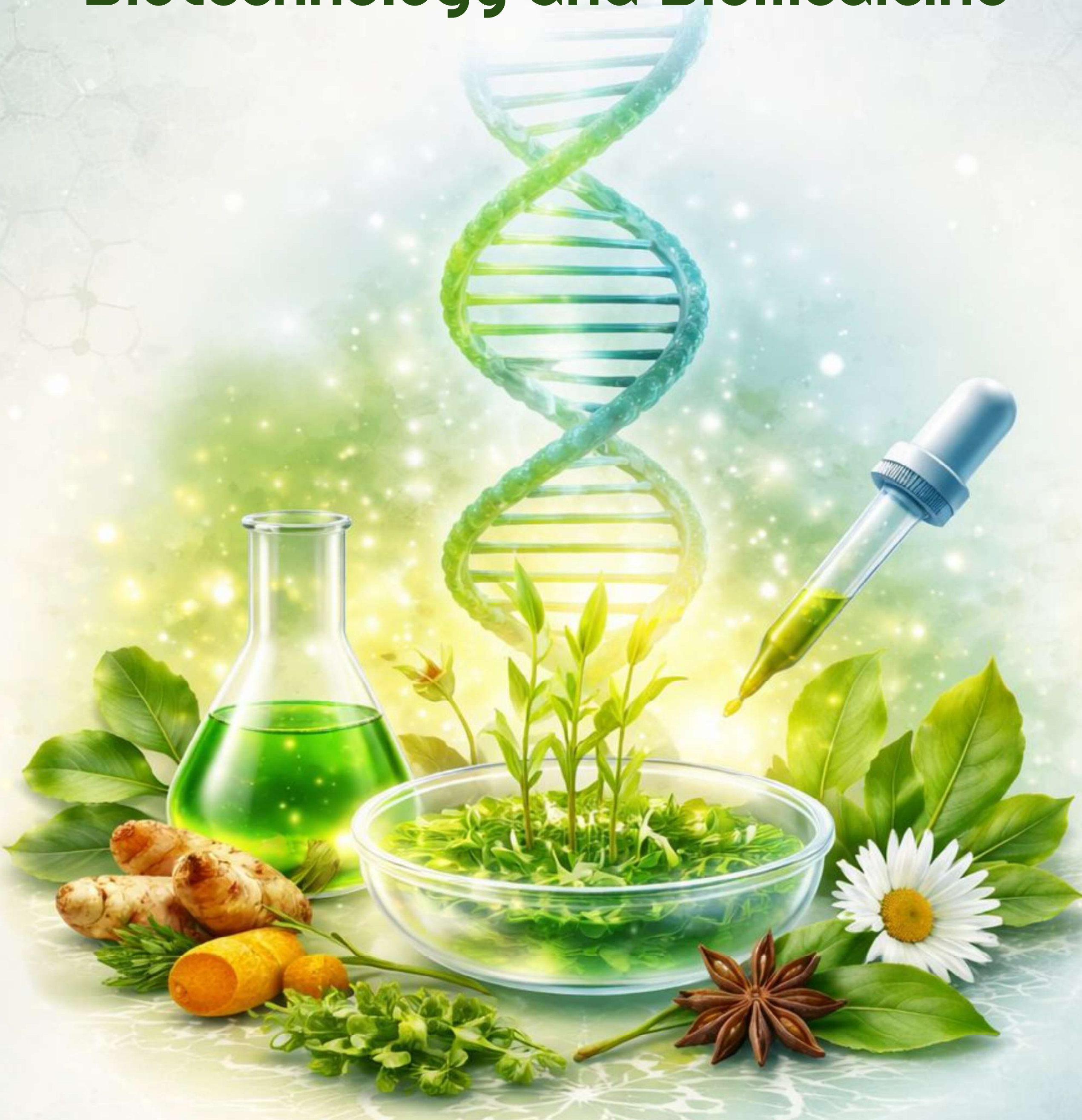
Emerging Bioactive Resources in Biotechnology and Biomedicine



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PREFACE

The rapid advancement of biotechnology and biomedicine has ushered in a transformative era in the exploration and utilization of bioactive resources derived from nature. The book *Emerging Bioactive Resources in Biotechnology and Biomedicine* is conceived as a comprehensive compilation that highlights innovative research directions, bridging fundamental biological insights with applied technological solutions. It brings together diverse studies that emphasize the immense potential of plant, microbial, and marine-derived bioactive compounds in addressing critical challenges in healthcare, environmental sustainability, and industrial applications.

This volume is structured to reflect the interdisciplinary nature of modern biotechnological research. The initial chapters focus on endophytic fungi and phytochemical investigations of medicinal plants, illustrating how naturally occurring bioactive compounds can be harnessed for therapeutic and preservative applications. Detailed studies on species such as *Commelina benghalensis*, *Euphorbia hirta*, *Heliotropium indicum*, and *Allium sativum* provide valuable insights into their chemical composition and pharmacological relevance, reinforcing the importance of traditional knowledge in contemporary biomedical research.

A significant portion of the book is dedicated to microbial and marine bioresources, which are increasingly recognized as rich reservoirs of novel compounds. Contributions on marine microorganisms and sponge metabolites explore their roles in environmental bioremediation and anticoagulant development, respectively. These chapters underscore the untapped potential of marine ecosystems in yielding next-generation bioactive agents with significant clinical and ecological applications.

The integration of biotechnology with sustainability is another central theme of this book. Chapters addressing enzyme-assisted waste degradation, microbial pigments, and agro-industrial waste utilization demonstrate innovative approaches to waste management and value addition. Furthermore, the development of biodegradable packaging systems, colorimetric sensor labels, and bio-based preservatives reflects the growing emphasis on eco-friendly and smart materials in food technology and environmental protection.

Advancements in material science and nanobiotechnology are also prominently featured. The inclusion of research on nanoencapsulation-driven hydrogel systems for autonomous concrete crack healing exemplifies how biological principles can be applied beyond traditional biomedical boundaries, extending into infrastructure and engineering domains. Such interdisciplinary innovations highlight the evolving scope of biotechnology in solving real-world problems.

Collectively, this book aims to serve as a valuable resource for researchers, academicians, and industry professionals seeking to explore emerging trends in bioactive resource utilization. By integrating phytochemistry, microbiology, nanotechnology, and environmental biotechnology, it provides a holistic perspective on the future directions of the field. It is hoped that this compilation will inspire further research, foster collaboration, and contribute to the development of sustainable and impactful biotechnological solutions.

We extend our sincere thanks to our publisher, Scientific Research Reports, Chennai, India, for their dedicated efforts in preparing this book and for ensuring the inclusion of enriched and high-quality technical content.

Wishes and Regards,

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CONTENTS

Chapter 12

Comparative Phytochemical and Bioactivity Analysis of Euphorbia Hirta and Gymnema Sylvestre Using Aqueous Extracts

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Abstract

Plant-derived bioactive compounds have gained considerable attention in recent years due to their diverse therapeutic properties and potential applications in modern healthcare. Medicinal plants such as *Euphorbia hirta* and *Gymnema sylvestre* are rich sources of phytochemicals including flavonoids, phenolics, saponins, and tannins, which exhibit significant antioxidant, anti-inflammatory, antimicrobial, and antidiabetic activities. Despite their pharmacological potential, the practical use of plant extracts in pharmaceutical and nutraceutical formulations is often limited by issues such as poor stability, low aqueous solubility, rapid degradation, and reduced bioavailability. To overcome these limitations, nano-encapsulation technologies have emerged as an effective strategy for improving the delivery and therapeutic performance of plant-derived bioactive. Among various nanocarrier materials, pectin a natural polysaccharide obtained from plant cell walls has attracted increasing interest due to its biodegradability, biocompatibility, non-toxicity, and excellent gel-forming properties. Pectin nanoparticles can be produced through ionic gelation using

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calcium chloride as a cross-linking agent, forming stable nanostructures capable of encapsulating sensitive phytochemicals. These nano formulations enhance the stability, solubility, and controlled release of plant bioactive, thereby improving their overall bioavailability and therapeutic efficacy. Furthermore, optimization techniques such as response surface methodology and Box–Behnken design enable the development of nanoparticles with desirable physicochemical characteristics. Characterization methods including particle size analysis, zeta potential measurement, and spectroscopic techniques provide insights into nanoparticle stability and encapsulation efficiency. This review highlights the principles of nano-encapsulation, the role of pectin as a natural polymer, and the potential biomedical, nutraceutical, and pharmaceutical applications of nano-encapsulated plant extracts while discussing current challenges and future research prospects.

Keywords: Pectin nanoparticles, Nano-encapsulation, Euphorbia hirta, Gymnema sylvestre; Phytochemicals.

1. Introduction

Scientists studied medicinal plants because they provide essential bioactive compounds which can treat medical conditions. The phytochemicals which include flavonoids phenolics alkaloids and saponins show antioxidant and antimicrobial and anti-inflammatory and antidiabetic properties which help to prevent and treat chronic diseases according to (Perveen and Safdar 2023). The two plants *Euphorbia hirta* and *Gymnema sylvestre* show their traditional medicine value through their respiratory disorder treatment and diabetes management capabilities. The medicinal power of plant extracts is restricted by their unstable nature and their poor solubility and their low bioavailability which requires scientists to develop better delivery methods that improve their medicinal power according to (Chowdhury et al., 2024).

1.1 Importance of Plant-Derived Bioactive Compounds

The medical field and traditional healthcare systems depend on plant-based bioactive compounds to create therapeutic medicines. The compounds display multiple biological functions through their combination of flavonoids phenolics alkaloids terpenoids and saponins which produce antioxidant activity and antimicrobial properties and anti-inflammatory effects and anticancer capabilities. The presence of these phytochemicals helps protect cells from oxidative stress and supports the prevention and management of chronic diseases including diabetes cardiovascular disorders and metabolic conditions. Plant bioactive substances receive extensive use in pharmaceutical products and nutraceuticals and functional foods because of their natural origin and safety and pharmacological properties according to (Srinivasan, 2023).

1.2 Medicinal Significance of *Euphorbia hirta*

Euphorbia hirta is a widely recognized medicinal herb used in traditional medicine for the treatment of respiratory disorders and gastrointestinal problems and skin infections. The plant contains various bioactive compounds which include flavonoids and phenolic acids and tannins and saponins which together create its pharmacological effects. The studies discovered that *Euphorbia hirta* extracts display strong antioxidant and antimicrobial and anti-inflammatory and antidiabetic effects. The organism's bioactivities originate from its phytochemicals which contain quercetin and gallic acid that protect against free radicals and block the growth of

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microbes. The plant provides valuable therapeutic properties which make it an essential resource for creating herbal medicines and nutraceutical products according to (Silwal, 2023).

1.3 Medicinal Significance of *Gymnema sylvestre*

Gymnema sylvestre serves as a primary therapeutic approach in traditional Ayurvedic medicine which practitioners use to manage diabetes and metabolic disorders. The plant contains several bioactive compounds which produce healing effects through its three main components gymnemic acids triterpenoids and flavonoids and saponins. The study by (Tiwari et al., 2017) shows that gymnemic acids reduce glucose absorption in the intestine while they stimulate insulin production which results in blood glucose regulation. The plant shows both antioxidant and anti-inflammatory functions which protect cells from oxidative stress and metabolic disruption. The medicinal properties of *Gymnema sylvestre* establish it as a key candidate for developing herbal medicines and nutraceutical product formulations.

1.4 Challenges in Stability and Bioavailability of Plant Extracts

Plant extracts possess strong therapeutic abilities, yet their use experiences multiple obstacles which stem from their stability issues and bioavailability problems. Phytochemicals become vulnerable to environmental factors because storage conditions include light and temperature and oxygen and enzymatic degradation, which causes their biological activity to diminish. The gastrointestinal tract absorption of plant-derived compounds remains restricted because they exhibit dual characteristics of poor water solubility and restricted absorption capacity. (Chowdhury et al., 2024) proved that these factors, which control herbal formulation effectiveness, can effectively reduce therapeutic results. The development of advanced delivery systems has become necessary because nano-encapsulation technology provides essential protection for bioactive compounds which additionally improves their stability and solubility and bioavailability.

2. Nano-Encapsulation Technology for Plant Bioactives

The advanced method of nano-encapsulation technology enables better stability and solubility and bioavailability of plant-based bioactive compounds. The technique uses nanoscale carriers to protect phytochemicals from environmental damage while they maintain controlled release of their active components. The small particle size increases surface area and enhances interaction with biological membranes which results in better absorption and therapeutic effectiveness. According to (Rosales and Fabi, 2023) natural polymers like pectin serve as common materials for nano-encapsulation because they provide biocompatibility and biodegradability while creating stable nanoparticles that pharmaceutical and nutraceutical industries can use.

2.1 Concept and Principles of Nano-Encapsulation

Nano-encapsulation describes the method which uses nanoscale carriers to contain bioactive compounds for their protection and enhanced delivery performance. The nano-encapsulation method operates by creating polymer or lipid-based nanoparticles which generate protective shells around delicate compounds. The nanocarriers enable precise and focused drug delivery while they also boost phytochemical solubility and bioavailability. The reduction of particle size to the nanometer range according to (McClements, 2020) study enables better interaction between bioactive compounds and

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biological membranes which results in improved absorption and therapeutic effects for pharmaceutical and nutraceutical products.

2.2 Types of Nano-Encapsulation Systems

Researchers have created different nano-encapsulation systems to achieve better bioactive compound delivery which maintains their stability. The primary system types used in this process are polymeric nanoparticles and liposomes and nano emulsions and solid lipid nanoparticles and nanogels. The various systems used for this purpose exhibit different characteristics because their structures and materials and methods of encapsulation differ from each other. People use polymeric nanoparticles to achieve controlled drug release whereas liposomes work for both hydrophilic and hydrophobic compound encapsulation. Bioactive molecules achieve better solubility and stability through nano emulsions when they exist in aqueous solutions. The nano-encapsulation system selection process requires researchers to evaluate the bioactive compound properties together with the desired application according to (Weiss et al., 2008).

2.3 Advantages of Nano-Encapsulation in Herbal Drug Delivery

The delivery of herbal medications benefits from Nano-encapsulation because it enhances the stability and solubility and bioavailability of plant-based active compounds. Phytochemicals display environmental sensitivity which results in poor body absorption; nano-encapsulation protects these compounds from degradation while increasing their therapeutic benefits. The nanoscale carriers provide a system which controls and precisely delivers active ingredients while minimizing the need for additional doses and decreasing the risk of side effects. The research conducted by (Sahoo et al., 2017) demonstrates that nano-encapsulation improves herbal formulations because it boosts their ability to deliver drugs through increased cellular absorption.

2.4 Applications of Nano-Encapsulation in Phytochemical Delivery

The delivery of phytochemicals through nano-encapsulation has become essential because this method improves the stability and solubility and controls the release of bioactive compounds which originate from plants. This technology functions in the pharmaceutical and nutraceutical and food sectors to improve the medicinal properties of herbal extracts. The process of encapsulation safeguards delicate phytochemicals from environmental destruction while it enhances their absorption in living organisms. The researchers (Fang and Bhandari, 2010) demonstrated that scientists use nano-encapsulation systems which include nano emulsions and polymeric nanoparticles to deliver antioxidants and polyphenols and other plant bioactive components because this method improves their bioavailability and functional performance.

3. Pectin as a Natural Polymer for Nano-Encapsulation

Pectin exists as a natural polysaccharide which plants produce to construct their cell walls and scientists have discovered its potential as a flexible polymer for nano-encapsulation because of its ability to interact safely with living organisms while breaking down into harmless substances. The gel creation process enables bioactive substances to be captured which results in their protection from degradation and the establishment of controlled release mechanisms. Pectin-based nanoparticles have been widely investigated for delivering plant extracts, drugs, and nutraceuticals, making them an eco-friendly and effective alternative to synthetic polymers. Studies

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show that pectin functional properties can be customized to meet the needs of particular delivery systems (Bhat et al., 2019).

3.1 Chemical Structure and Properties of Pectin

Pectin functions as a heteropolysaccharide which consists of galacturonic acid units that connect through α-(1→4) glycosidic bonds and its gelling behavior depends on its different levels of methyl esterification (Voragen et al. 2009). The substance contains rhamnose and arabinose as well as galactose which function as neutral sugar side chains that determine its ability to dissolve and its thickness and its ability to stabilize mixtures. The structural diversity of pectin allows for modification of its physicochemical characteristics which makes the substance suitable for forming nanoparticles and gels which serve as delivery systems. Its pH-sensitive nature also enables controlled release of bioactive compounds that have been encapsulated.

3.2 Biocompatibility and Biodegradability of Pectin

Pectin demonstrates high biocompatibility which produces almost no immune or cell damage reactions, making it suitable for medical use and drug delivery systems according to Sutherland (2001). The material comes from natural sources which pectinolytic enzymes can break down through enzymatic processes throughout the digestive system, leading to complete environmental-friendly degradation without creating any harmful substances. The material provides safe methods to encapsulate bioactive substances for oral use and topical application and systemic delivery. The biodegradation rate of pectin can be controlled through chemical changes and cross-linking processes, which create a mechanism for controlled therapeutic release.

3.3 Mechanism of Pectin-Based Nanoparticle Formation

Researchers create pectin-based nanoparticles through ionic gelation processes which use pectin's negatively charged carboxyl groups to bind with divalent cations like calcium for network creation (Mustafa et al., 2019). The process produces a stable nanoparticulate system which can trap bioactive substances. The properties of pectin concentration and molecular weight and degree of esterification determine the characteristics of particles which include their size and shape and their ability to encapsulate materials. The approach provides security for delicate plant chemicals while enabling their precise distribution through specialized delivery methods.

3.4 Role of Calcium Chloride as a Cross-Linking Agent

Calcium chloride ($CaCl_2$) serves as the main cross-linking agent which enables pectin-based nanoparticles to form through its interaction with the carboxyl groups found in pectin chains, which creates ionic gelation (Kumar et al., 2020). The nanoparticle structure achieves stabilization through cross-linking, which leads to improved mechanical strength and better control over the release process of the contained bioactive substances. The study found that both $CaCl_2$ concentration and solution pH level directly impacted particle size and encapsulation efficiency, along with release kinetics, which made these factors essential for developing effective pectin-based nanocarrier systems designed to deliver drugs.

4. Methods, Optimization, and Characterization of Pectin Nanoparticles

The preparation of pectin nanoparticles requires specific methods which scientists need to optimize through various techniques for analyzing their performance in bioactive compound encapsulation

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and controlled release. The common methods for creating nanoparticles include ionic gelation and emulsion-diffusion and coacervation (Patel et al., 2021). The process of optimization examines multiple factors which include polymer concentration cross-linker amount stirring rate and pH until the target particle size and stability requirements are met. The research team uses dynamic light scattering (DLS) and scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) to evaluate particle characteristics which include morphology and size and surface charge and chemical interactions to establish reproducibility for drug delivery systems.

4.1 Methods of Nano-Encapsulation for Plant Extracts

The process of nano-encapsulation protects bioactive compounds in plant extracts through multiple techniques which increase their bioactive compound availability. The most common methods include ionic gelation which depends on the electrostatic forces between pectin and its cross-linking materials (Ribeiro et al., 2020) and emulsion diffusion which creates nanoparticles through the distribution of an extract within a polymeric liquid (Kumar et al., 2019) and coacervation which uses polymeric materials to create separate phases for extract trapping. When selecting methods for plant bioactive substances researchers use spray-drying and nanoprecipitation based on the specific physicochemical characteristics of the substances and their desired release patterns.

4.2 Optimization Techniques in Nano formulation

The process of optimizing nano formulations needs to be completed because it serves as the foundation for achieving high encapsulation efficiency and controlled release and particle stability. The Response

Surface Methodology (RSM) methods enable researchers to assess the effects of formulation variables and their combined effects on product development (Patel et al., 2020). The factorial design method enables researchers to determine which factors most strongly influence the size of nanoparticles and their ability to carry drugs. The central composite design and Box–Behnken design methods enable researchers to optimize three parameters which include polymer concentration and cross-linker ratio and process parameters for achieving reproducible and effective nano-encapsulation of plant bioactive substances (Kaur et al., 2021).

4.3 Characterization Techniques for Nanoparticles

The process of nanoparticle characterization enables scientists to determine three essential properties which include particle size, particle shape, and surface charge, along with particle stability, since these factors determine two biological activities. Dynamic light scattering (DLS) provides measurements of particle dimensions together with polydispersity index results. The techniques of scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide researchers with direct visual access to examine surface details of materials. Zeta potential analysis evaluates surface charge properties together with the ability of colloids to maintain their stable state, while Fourier-transform infrared spectroscopy (FTIR) demonstrates the chemical interactions that occur between plant extracts and polymer matrices according to Rao and Reddy 2022. The methods which scientists use in their research enable precise optimization of pectin-based nanoparticles for herbal delivery systems.

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4.4 Encapsulation Efficiency and In-Vitro Release Studies

The encapsulation efficiency (EE) measurement assesses how many bioactive compounds nanoparticles successfully capture which affects both their stability and therapeutic performance. In-vitro release studies assess the controlled release of these compounds under simulated physiological conditions which researchers conduct using various pH buffers that imitate gastrointestinal environments (Sharma & Verma, 2020). The release profile measurement uses analytical techniques which include UV–vis spectrophotometry and HPLC and fluorescence spectroscopy to deliver essential data needed for developing effective sustained delivery systems that use plant extracts.

5. Applications, Challenges, and Future Perspectives

The process of nano-encapsulation for plant bioactive substances creates multiple applications which include bettering nutraceutical and pharmaceutical products and improving targeted drug delivery systems along with their bioavailability (Patel et al. 2021). Biomedical applications include antimicrobial, anticancer, and anti-inflammatory therapies, which use controlled release systems to decrease their toxic effects on patients (Singh & Sharma 2020). The field has made progress but still needs solutions for three main problems which include difficulties in production at larger scales and requirements needed for regulatory approval and maintaining product stability while keeping costs down. Future research will study multifunctional nanocarriers together with precision delivery systems which use natural polymers such as pectin to create safer and more effective phytochemical treatments.

5.1 Nutraceutical and Pharmaceutical Applications

The process of nano-encapsulation enhances the three properties of plant bioactive compounds because it protects their stability and improves their solubility and bioavailability which results in better performance for nutraceutical and pharmaceutical applications. The method of encapsulation enables the precise distribution of polyphenols flavonoids and alkaloids which protects these substances from being destroyed in the gastrointestinal tract while their medicinal properties become stronger (Rao & Singh 2019). The systems establish specific delivery routes which enable continual product distribution throughout the duration of treatment while assisting patients in following their medication regimen.

5.2 Biomedical Applications of Pectin-Based Nanocarriers

Pectin-based nanocarriers have gained attention in biomedical applications because they possess biocompatibility and biodegradability and non-toxic properties according to (Ahmed et al., 2021). The system functions through targeted drug delivery and cancer treatment and controlled release of bioactive compounds which help minimize systemic side effects. Pectin nanoparticles demonstrate their multiple applications in contemporary medicine through their ability to improve wound healing and enhance antimicrobial activity and function as vaccine and gene delivery systems.

5.3 Future Research Directions and Prospects

Future research in nano-encapsulation should focus on developing stimuli-responsive and targeted delivery systems to improve site-specific bioactive release (Singh et al., 2022). The use of green synthesis methods will improve sustainability while decreasing toxic

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effects. The combination of advanced characterization techniques and real-time in vivo imaging will enable researchers to track both nanoparticle movement and their medical effectiveness. The research will investigate how plant bioactive compounds work together with nanocarriers to enhance medical results while developing pectin-based nano formulations for regulatory safety assessment.

6. Conclusion

The therapeutic properties of plant-based bioactive compounds stem from their capacity to fight oxidative stress and reduce inflammation and control diabetes symptoms. The clinical effectiveness of these compounds is obstructed by their inherent challenges which include unstable compounds and their difficulty to dissolve and their restricted ability to be absorbed by the body. Nano-encapsulation has emerged as a promising approach to address these limitations by protecting bioactive from degradation, enhancing solubility, and enabling controlled and targeted release. The natural polymer pectin enables biocompatible and biodegradable properties while forming nanoparticles through its calcium chloride cross-linking process. The combination of ionic gelation and emulsification and spray drying methods enables encapsulation while optimization and characterization methods guarantee product consistency and operational performance. Pectin-based nanoparticles have shown promise in nutraceutical, pharmaceutical, and biomedical applications, improving therapeutic outcomes and patient compliance. The process of scalability and obtaining regulatory approvals and conducting safety assessments present ongoing challenges for researchers. Future research should investigate delivery systems that respond to stimuli and protect the environment during synthesis while conducting in vivo safety and efficacy studies.

The combination of plant bioactive compounds with pectin-based nano-encapsulation systems represents a vital opportunity to enhance both contemporary drug delivery methods and treatment practices.

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