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Review Article

Nanostructure properties and potential biomedical applications of *Nelumbo nucifera Gaertn* extracts

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Abstract

Nelumbo nucifera Gaertn (NNG), commonly known as the sacred lotus, holds immense potential in biomedical applications due to its rich bioactive compounds. In recent years, nanotechnology has emerged as a powerful tool for exploring the nano-structural properties of natural extracts and harnessing their biomedical benefits. This review delves into the nano-structural properties of NNG extracts and their potential applications in biomedicine. We discuss various extraction techniques and characterisation methods like SEM, TEM, DLS, XRD, AFM, NMR, and SARS employed to elucidate the nanostructures present in NNG extracts. Furthermore, we explore the biomedical applications of these nanostructures, including drug delivery, tissue engineering, imaging, and biosensing. Through a comprehensive examination of current research findings, this review highlights the promising role of NNG extracts in nanomedicine and underscores the need for further investigation to unlock their full therapeutic potential.

Keywords: *Nelumbo nucifera Gaertn*, Biomedical applications, Nanostructure characterization, Drug delivery system, Nanomedicine, Future challenges

Introduction

Nanotechnology has revolutionized various fields, including biomedical research, by offering unprecedented opportunities for the development of innovative therapeutic and diagnostic strategies [1]. Natural products, particularly plant extracts, have garnered significant attention in the quest for novel biomedical solutions due to their diverse bioactive compounds [2]. Among these, *Nelumbo nucifera Gaertn* (NNG), commonly known as the sacred lotus, has emerged as a promising candidate owing to its rich pharmacological profile and historical significance in traditional medicine [3]. The sacred lotus, native to Asia and parts of Oceania, has been revered for centuries for its symbolic and medicinal value. It is known to contain a plethora of bioactive compounds, including alkaloids, flavonoids, phenolic acids, and polysaccharides, which exhibit various biological activities such as antioxidant, anti-inflammatory, antimicrobial, and anticancer properties [4,5]. Recent advancements in nanotechnology have enabled researchers to explore the nanostructural properties of natural extracts like NNG and harness their therapeutic potential in a more targeted and effective manner [6].

This review aims to provide a comprehensive overview of the nanostructural properties of NNG extracts and their potential biomedical applications. We will discuss the extraction techniques employed to isolate bioactive compounds from NNG, as well as the characterization methods used to elucidate their nanostructures. Furthermore, we will explore the emerging biomedical applications of these nanostructures, including drug delivery systems, tissue engineering scaffolds, imaging probes, and biosensors [7]. By examining the current state of research in this field, we seek to highlight the promising role of NNG extracts in nanomedicine and underscore the importance of further investigations to fully harness their therapeutic potential. Ultimately, understanding the nano-structural properties of natural extracts like NNG opens up new avenues for the development of advanced biomedical technologies with enhanced efficacy and reduced side effects.

Background on *Nelumbo nucifera Gaertn*

NNG, commonly known as the sacred lotus, is a plant species belonging to the *Nelumbonaceae* family [8]. It is native to various regions of Asia, including India, China, Japan, and Southeast Asia, and is also found in parts of Oceania. The sacred lotus holds profound cultural and religious significance in many Asian countries and has been revered for its beauty, purity, and medicinal properties for centuries. The sacred lotus is an aquatic plant characterized by large, round leaves that float on the surface of water and striking flowers that can vary in colour from white to pink to pale yellow. Its distinctive flowers have been depicted in various art forms and are associated with spiritual symbolism in many cultures.

In addition to its cultural importance, NNG has a long history of use in traditional medicine systems such as Ayurveda and Traditional Chinese Medicine (TCM) [9]. Different parts of the plant, including the flowers, seeds, leaves, and rhizomes, have been utilized for their medicinal properties [8]. The plant contains a diverse array of bioactive compounds, including alkaloids, flavonoids, phenolic acids, polysaccharides, and vitamins, which contribute to its pharmacological effects [10].

NNG extracts have been reported to exhibit various biological activities, including antioxidant, anti-inflammatory, antimicrobial, hepatoprotective, neuroprotective, and anticancer properties. These pharmacological effects have attracted significant interest from researchers seeking to explore the potential therapeutic applications of the sacred lotus in modern medicine [11]. Moreover, with the advent of advanced analytical techniques and nanotechnology, researchers have begun to delve deeper into the nanostructural properties of NNG extracts. Understanding the nanostructures present in these extracts is crucial for elucidating their mechanisms of action and for developing innovative biomedical applications, such as drug delivery systems, tissue engineering scaffolds, and diagnostic agents [12]. Overall, NNG represents a fascinating botanical species with a rich history and diverse pharmacological potential. Further research into its bioactive constituents and nanostructural properties holds promise for the development of novel therapeutic interventions and biomedical technologies [13].

Nanotechnological Approaches in Biomedical Research

Nanotechnology has emerged as a revolutionary field in biomedical research, offering innovative approaches to address various healthcare challenges. By harnessing the unique properties of materials at the nanoscale, nanotechnological approaches enable precise manipulation and control over biological systems, facilitating the development of novel diagnostic tools, therapeutic agents, and regenerative medicine strategies [14,15].

One of the key applications of nanotechnology in biomedicine is in the field of drug delivery. Nanoscale drug delivery systems, such as nanoparticles, liposomes, and polymeric micelles, offer advantages such as enhanced drug solubility, improved bioavailability, prolonged circulation time, and targeted delivery to specific tissues or cells [16,17]. These nanostructured carriers can encapsulate a wide range of therapeutic agents, including small molecules, proteins, nucleic acids, and peptides, allowing for precise control over drug release kinetics and localization within the body [18]. Additionally, functionalization of nanoparticles with targeting ligands enables selective delivery to disease sites, reducing off-target effects and minimizing systemic toxicity [19].

Nanotechnology also plays a pivotal role in the development of advanced imaging techniques for biomedical applications. Nanoparticle-based contrast agents offer superior imaging capabilities compared to traditional contrast agents, allowing for high-resolution imaging of anatomical structures, molecular processes, and cellular interactions [20]. Quantum dots, gold nanoparticles, iron oxide nanoparticles, and carbon nanotubes are among the nanoparticles utilized as contrast agents in various imaging modalities, including magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), and optical imaging [21]. Furthermore, multifunctional nanoparticles capable of simultaneous imaging and therapy, known as theragnostic nanoparticles, hold great promise for personalized medicine approaches by enabling real-time monitoring of treatment efficacy and disease progression [22].

In addition to drug delivery and imaging, nanotechnology offers innovative solutions for regenerative medicine and tissue engineering applications. Nanostructured scaffolds, fabricated using techniques such as electrospinning, self-assembly, and 3D bioprinting, mimic the extracellular matrix (ECM) architecture and provide a conducive microenvironment for cell adhesion, proliferation, and differentiation [23]. Functionalization of scaffolds with bioactive molecules, growth factors, and signalling peptides enhances their regenerative capacity and promotes tissue regeneration in damaged or diseased tissues [24]. Moreover, nanomaterial-based approaches for stem cell therapy, gene editing, and organ-on-a-chip platforms hold immense potential for advancing our understanding of disease mechanisms and accelerating the development of novel therapies [25]. The nanotechnological approaches have revolutionized biomedical research by offering versatile tools for drug delivery, imaging, regenerative medicine, and disease modelling. Continued interdisciplinary efforts in nanotechnology and biomedicine hold promise for addressing unmet medical needs, improving patient outcomes, and advancing the forefront of healthcare innovation [26].

Nanostructural Characterization of *Nelumbo nucifera Gaertn* Extracts

The nanostructural characterization of NNG extracts is a crucial aspect of understanding their potential biomedical applications [27]. Various analytical techniques are employed to elucidate the nanostructures present in these extracts, providing insights into their physical, chemical, and morphological properties at the nanoscale [28]. One common technique used for nano-structural characterization is scanning electron microscopy (SEM), which allows for high-resolution imaging of the surface morphology of nanoparticles and nanostructures present in the extracts. SEM provides information about the size, shape, and surface features of the nanostructures, helping researchers visualize and analyze their structural characteristics [29].

Transmission electron microscopy (TEM) is another powerful tool for nano-structural characterization, enabling direct visualization of individual nanoparticles and nanostructures with nanometre-scale resolution. TEM provides detailed information about the internal structure, crystallinity, and composition of the nanostructures, facilitating their thorough characterization [30]. Dynamic light scattering (DLS) is employed to determine the hydrodynamic size distribution of nanoparticles in solution. By measuring the intensity fluctuations of scattered light caused by the Brownian motion of nanoparticles, DLS provides information about the size distribution and polydispersity of nanostructures in the extract [31].

X-ray diffraction (XRD) analysis is utilized to investigate the crystalline structure and phase composition of nanoparticles and nanomaterials present in the extracts. XRD patterns reveal characteristic diffraction peaks corresponding to the crystal lattice planes of the nanostructures, allowing researchers to identify the crystalline phases and assess their purity and crystallinity [32]. Fourier-transform infrared spectroscopy (FTIR) is employed to analyze the chemical composition, and functional groups present in the nanostructures. FTIR spectra provide information about the vibrational modes of chemical bonds in the extract, enabling the identification of specific functional groups and molecular constituents [33].

Furthermore, techniques such as atomic force microscopy (AFM), nuclear magnetic resonance (NMR) spectroscopy, and surface-enhanced Raman spectroscopy (SERS) can also be utilized for nanostructural characterization, providing complementary information about the physical, chemical, and mechanical properties of NNG extracts at the nanoscale [34,35]. In summary, the nanostructural characterization of NNG extracts involves a multidisciplinary approach utilizing various analytical techniques to elucidate the size, shape, morphology, composition, and properties of nanostructures present in the extracts. This comprehensive characterization is essential for understanding the nanostructural features of the extracts and exploring their potential biomedical applications, including drug delivery, imaging, and tissue engineering.

Biomedical Applications of *Nelumbo nucifera Gaertn* Extracts

Biomedical applications of NNG extracts encompass a broad spectrum, from antioxidant and anti-inflammatory effects to antimicrobial and anticancer activities. These extracts hold promise for therapeutic interventions and drug development, offering potential solutions for various diseases and conditions. Additionally, their nanostructural properties enable innovative applications in drug delivery, tissue engineering, and diagnostic imaging, further expanding their biomedical utility. Continued research into the bioactive compounds and nanostructural properties of NNG extracts may lead to the development of novel treatments and biomedical technologies, ultimately improving human health and well-being [27,36].

Drug delivery systems

Drug delivery systems play a pivotal role in modern medicine, facilitating the targeted and controlled release of therapeutic agents to specific sites within the body. NNG extracts offer a promising platform for the development of innovative drug delivery systems due to their bioactive compounds and unique nano-structural properties. By harnessing these properties, researchers aim to enhance the efficacy, safety, and specificity of drug delivery while minimizing side effects and improving patient outcomes [37].

One approach to utilizing NNG extracts in drug delivery is through the formulation of nanoparticles or nanocarriers. Nanoparticles derived from NNG extracts can encapsulate a variety of therapeutic agents, including small molecules, proteins, nucleic acids, and peptides. These nanoparticles can be engineered to possess specific physicochemical properties, such as size, surface charge, and surface chemistry, which influence their behavior in biological systems and their interactions with target cells or tissues [38].

The nanostructural properties of NNG extracts, characterized by nanoparticles and nanostructures, enable efficient encapsulation and delivery of therapeutic agents. Moreover, the presence of functional groups on the surface of nanoparticles derived from NNG extracts facilitates surface modification and functionalization with targeting ligands, allowing for site-specific delivery to diseased tissues or cells. This targeted approach minimizes off-target effects and enhances the therapeutic index of drugs, leading to improved efficacy and reduced toxicity [39].

Furthermore, the sustained-release properties of nanoparticles derived from NNG extracts prolong the therapeutic effect of drugs, leading to prolonged drug retention and reduced dosing frequency. This not only enhances patient compliance but also minimizes fluctuations in drug concentration, optimizing therapeutic outcomes. Additionally, the biocompatibility and biodegradability of nanoparticles derived from NNG extracts ensure minimal adverse effects and facilitate clearance from the body, making them suitable for clinical applications [40].

In addition to nanoparticle-based drug delivery systems, NNG extracts can also be utilized in other drug delivery platforms, such as liposomes, micelles, and hydrogels. These delivery systems offer distinct advantages in terms of drug loading capacity, stability, and release kinetics, allowing for tailored drug delivery strategies based on the desired therapeutic outcome [41].

Overall, the utilization of NNG extracts in drug delivery systems represents a promising approach to improving the efficacy and safety of therapeutic agents. By leveraging the bioactive compounds and nanostructural properties of these extracts, researchers can develop targeted, controlled-release formulations that enhance therapeutic outcomes while minimizing adverse effects. Continued research in this area holds the potential to revolutionize drug delivery and advance the treatment of various diseases.

Therapeutic agents

NNG extracts offer a rich source of bioactive compounds with diverse pharmacological properties, making them promising candidates for the development of therapeutic agents. These bioactive compounds, including alkaloids, flavonoids, phenolic acids, and polysaccharides, exhibit a wide range of biological activities that hold potential for the treatment and management of various diseases and conditions [42].

One therapeutic application of NNG extracts is in the field of antioxidant therapy. The presence of potent antioxidants, such as flavonoids and phenolic acids, enables these extracts to scavenge free radicals and reduce oxidative stress, which is implicated in the pathogenesis of numerous diseases, including cardiovascular diseases, neurodegenerative disorders, and cancer. By neutralizing reactive oxygen species and inhibiting oxidative damage to cells and tissues, NNG extracts may help prevent disease progression and alleviate symptoms associated with oxidative stress-related conditions [43,44].

Furthermore, the anti-inflammatory properties of NNG extracts make them valuable candidates for the development of anti-inflammatory agents. Chronic inflammation is a key contributor to the pathogenesis of various diseases, including arthritis, inflammatory bowel disease, and asthma. Bioactive compounds present in NNG extracts exert anti-inflammatory effects by inhibiting pro-inflammatory mediators and signaling pathways, thereby reducing inflammation and alleviating associated symptoms. These anti-inflammatory properties may offer therapeutic benefits for individuals suffering from inflammatory conditions, improving their quality of life and overall well-being [44].

Moreover, NNG extracts exhibit notable antimicrobial activity against a wide range of pathogens, including bacteria, fungi, and viruses. The antimicrobial compounds present in these extracts, such as alkaloids and tannins, exert inhibitory effects on microbial growth and proliferation, making them potential candidates for the development of antimicrobial agents. By targeting pathogenic microorganisms and inhibiting their virulence mechanisms, NNG extracts may help combat infectious diseases and reduce the spread of antimicrobial resistance [45].

In addition to their antioxidant, anti-inflammatory, and antimicrobial properties, NNG extracts demonstrate promising anticancer activity. Various bioactive constituents present in these extracts exhibit cytotoxic effects on cancer cells, induce apoptosis, inhibit tumor growth, and suppress metastasis. Additionally, NNG extracts may enhance the efficacy of conventional chemotherapeutic agents while reducing their toxicity, offering a potential adjunctive therapy for cancer treatment. These anticancer properties highlight the therapeutic potential of NNG extracts in the fight against cancer and the development of novel cancer therapies. Overall, NNG extracts hold promise as sources of therapeutic agents for a wide range of diseases and conditions. Their diverse pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities, make them valuable candidates for further research and development. Continued investigation into the bioactive compounds present in NNG extracts and their mechanisms of action may lead to the identification of novel therapeutic agents with potential clinical applications [46].

Imaging agents

NNG extracts possess unique nanostructural properties that make them promising candidates for the development of imaging agents. The presence of nanoparticles and nanostructures derived from these extracts can be harnessed to enhance various imaging modalities, enabling non-invasive visualization of biological processes, disease pathology, and therapeutic responses. Here, we explore the potential of NNG extracts as imaging agents across different imaging techniques. One of the most commonly utilized imaging modalities in biomedical research and clinical practice is magnetic resonance imaging (MRI). Nanoparticles derived from NNG extracts can serve as contrast agents for MRI, enhancing the visibility of tissues and organs in magnetic resonance images. These nanoparticles, such as iron oxide nanoparticles, possess unique magnetic properties that influence the relaxation rates of nearby water molecules, leading to changes in signal intensity and improved contrast in MRI images. By functionalizing these nanoparticles with targeting ligands, researchers can achieve targeted imaging of specific cells or tissues, enabling early detection and precise localization of pathological abnormalities [47].

In addition to MRI, nanoparticles derived from NNG extracts can also be employed as contrast agents for other imaging modalities, such as computed tomography (CT) and ultrasound imaging. Nanoparticles with high X-ray attenuation properties can enhance the contrast in CT images, providing detailed anatomical information and aiding in the diagnosis of various diseases. Similarly, ultrasound contrast agents derived from NNG extracts can enhance the echogenicity of tissues, improving the sensitivity and specificity of ultrasound imaging for detecting lesions and monitoring disease progression.

Furthermore, the optical properties of nanoparticles derived from NNG extracts make them suitable for optical imaging techniques, such as fluorescence imaging and photoacoustic imaging. Nanoparticles with inherent fluorescence or photoacoustic properties can be utilized as imaging probes to visualize biological processes and molecular targets with high sensitivity and spatial resolution. Moreover, functionalization of these nanoparticles with targeting moieties allows for specific labelling and imaging of cellular or molecular targets, enabling precise localization and characterization of diseased tissues [48]. Overall, the nanostructural properties of NNG extracts offer a versatile platform for the development of imaging agents across different imaging modalities. By harnessing these properties, researchers can engineer nanoparticles with tailored physicochemical properties and imaging capabilities, enabling enhanced visualization and characterization of biological structures and processes. Continued research and development in this area hold promise for advancing imaging technologies and improving their utility in biomedical research, disease diagnosis, and patient care [49].

Challenges and Future Directions

Challenges and future directions in the utilization of NNG extracts in biomedical applications revolve around several key areas. Firstly, there is a need for a comprehensive understanding of the bioactive compounds present in these extracts and their mechanisms of action. Further research is necessary to elucidate the pharmacological properties and therapeutic potential of individual constituents, as well as their synergistic interactions. Secondly, while the nanostructural properties of NNG extracts hold promise for drug delivery, imaging, and tissue engineering, challenges remain in optimizing their formulation and stability. Developing scalable and reproducible fabrication methods for nanostructured materials derived from these extracts is essential for their translation into clinical applications.

Moreover, the safety and biocompatibility of NNG extracts-based formulations must be rigorously evaluated to ensure their suitability for biomedical use. Preclinical studies are needed to assess potential toxicity, immunogenicity, and long-term effects, paving the way for clinical trials and regulatory approval. In addition, challenges exist in achieving targeted delivery and controlled release of therapeutic agents using NNG extracts-based drug delivery systems. Further optimization of nanoparticle surface modifications and targeting strategies is required to enhance specificity and efficacy while minimizing off-target effects.

Furthermore, interdisciplinary collaboration and knowledge exchange are essential for advancing research in this field. Integrating expertise from various disciplines, including pharmacology, nanotechnology, and biomaterials science, can accelerate the development of innovative biomedical applications of NNG extracts. Looking ahead, future directions in the utilization of NNG extracts in biomedical applications include exploring novel delivery routes, such as transdermal and mucosal delivery, as well as investigating their potential in emerging areas such as regenerative medicine and personalized medicine. Continued innovation and investment in research and development efforts are crucial for unlocking the full therapeutic potential of NNG extracts and realizing their impact on human health.

Conclusion

In conclusion, the nanostructural properties of NNG extracts offer immense potential for a wide range of biomedical applications. Through meticulous characterization and understanding of these nanostructures, researchers have uncovered opportunities to harness the therapeutic properties of this botanical species for various medical purposes. From antioxidant and anti-inflammatory effects to antimicrobial and anticancer activities, NNG extracts demonstrate diverse pharmacological benefits that can be leveraged for disease management and treatment. Moreover, their nanostructural features enable innovative approaches in drug delivery, tissue engineering, and diagnostic imaging, promising enhanced efficacy and specificity in biomedical interventions.

However, realizing the full potential of NNG extracts in biomedicine requires addressing several challenges, including optimization of formulation, evaluation of safety, and advancement of targeted delivery strategies. Furthermore, interdisciplinary collaboration and continued research efforts are essential for translating these findings from the laboratory to clinical practice.

In essence, the exploration of the nanostructural properties and potential biomedical applications of NNG extracts represents a promising avenue for advancing healthcare and improving patient outcomes. With further innovation and investment in research, these botanical extracts have the potential to revolutionize medical treatments and contribute to the advancement of personalized and precision medicine approaches.

Declaration

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Author Contribution

Rakesh Sahu conceived the study concept, while Bhaskar Sahu collected the data, and Bina Gidwani prepared the format of the article.

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