Unraveling the Merits of Zein Nanoparticles: A Review on its Biodegradability, Biocompatibility, and Drug Delivery Applications

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ABSTRACT

Zein, a protein fraction derived from corn, has emerged as a promising material for developing biocompatible and biodegradable nanocarriers for drug delivery applications. This review article explores the advantages of zein nanoparticles, including their biodegradability, biocompatibility, amphiphilic nature, and potential for controlled drug release. We delve into the various characterization methods employed to evaluate zein nanoparticles, focusing on aspects like size, shape, surface charge, and internal structure. Additionally, the review discusses techniques for drug loading and encapsulation efficiency, crucial factors for designing effective nanoparticles for targeted drug delivery. The broad applicability of zein nanoparticles in biomedicine is then addressed. We explore their potential for enhancing drug solubility, delivering therapeutics to specific tissues and cells, and protecting drugs from degradation during transport. The review highlights the exciting possibilities of zein nanoparticles in targeted cancer therapy, protein and enzyme delivery, gene therapy, and treatment of infectious diseases. However, challenges remain in achieving consistent high drug loading, efficient targeting, large-scale production, and preventing unintended blood vessel occlusions. The review concludes by emphasizing the need for further research in these areas, including advanced characterization techniques, exploration of combinations with other biocompatible polymers, and advancements in therapeutic applications like gene therapy and protein delivery. By addressing these challenges, zein nanoparticles hold immense potential to revolutionize drug delivery systems in the future.

Keywords: Nanoparticles, Drug delivery, Biocompatible, Biodegradable, Targeted therapy, Biomedicine, Nanocarriers, Gene therapy

1. INTRODUCTION

The field of drug delivery has undergone a significant shift, focusing on targeted delivery where the release occurs at a controlled rate (Crommelin, & Florence, 2013). Nanoparticles (NPs) have emerged as superior carriers for drug delivery, outperforming traditional methods (Chandrakala et al., 2022). Their diminutive size offers enhanced biodistribution, selective delivery to vital tissues, and the ability to overcome biological barriers (Pramanik et al., 2020). Among all materials used in NP production, zein, a protein from corn, has gained substantial attention due to its inherent biocompatibility, biodegradability, and multifunctionality (Jaski et al., 2022). This review provides an in-depth analysis of recent advancements in zein-based NPs as drug carriers (Bahamonde et al., 2023). We discuss the unique properties of zein that make it an excellent choice for NP production (Tivano & Chiono, 2023). We then delve into the fabrication techniques and properties of zein-based NPs, highlighting the key factors that influence their characteristics (Borchers et al., 2021; Sahu et al., 2023).

After discussing fabrication methods, we examine the essential performance characterization techniques used to assess zein NPs (Wang et al., 2023). These techniques are crucial for determining the size, shape, and other physicochemical properties of the nanoparticles, such as surface area, drug loading, and release kinetics (Nemutlu et al., 2019). Understanding these properties is fundamental to the NP design process and ensures the effectiveness of drug delivery using NPs (Scioli et al., 2020). This review aims to explore the diverse biomedical applications of zein-based nanoemulsions (Mahanty et al., 2021). We discuss their potential use in drug delivery, highlighting their ability to deliver drugs to specific tissues or organs, thereby reducing systemic exposure and enhancing therapeutic efficacy (Adepu & Ramakrishna et al., 2021). The paper will evaluate the use of zein nanoparticles in various clinical settings and explore potential applications such as cancer therapy, gene therapy, and the delivery of antibiotics, vaccines, and imaging agents (Abdelsalam et al., 2021). We will also discuss strategies to achieve the desired targeting functionality of zein NPs (Hassan et al., 2022). This is achieved by using different ligands and receptor molecules attached to the NPs' surface that can bind to target cell receptors (Sanità et al., 2022). This approach allows for significant advancements in drug delivery and minimizes off-target effects (Jia et al., 2023).

This review will not only cover traditional applications but will also focus on past and future applications of zein NPs as theranostics (combining therapy and diagnostics) and controlled release of biomolecules (Zambonino et al., 2023). Along with this, we will elaborate on the current challenges and future possibilities associated with zein-based NPs (Oleandro et al., 2024). These strategies include targeted measures to stabilize them, tailor their release rates, and address potential hurdles for upscaling during clinical application (Mehta et al., 2023). The focus of this review is to present a comprehensive assessment of the latest techniques available in zein-based nanoparticles for drug delivery, with the aim of serving as a robust platform for researchers and scientists in the field (Almeida et al., 2023; Pérez et al., 2022). We believe that the research described will contribute significantly to study enhancement and, consequently, to the creation of clinically relevant zein-based drug carriers (Raza et al., 2020).

The drug delivery field is constantly evolving, necessitating the search for solutions to the disadvantages presented by conventional techniques (Park et al., 2022). Nanoparticles (NPs) have shown great potential, as well as the ability of scientists to target specific receptors, overcome limitations in biological barriers, and improve bioavailability (Cao et al., 2020). Zein, a protein derived from corn kernels, is a common choice in NP production due to its natural biocompatibility and biodegradability and its multifunctionality, which includes blending natural products, providing a protective barrier against UV, controlling drug release, therapeutic properties, and packaging (Tivano & Chiono et al., 2023).

In this article, we explore the emerging zein-based NPs for drug delivery applications in recent research progress (Preetam et al., 2024). The main aim of the article is to provide a broad but systematic overview of these remarkable materials, which include the beneficial features of zein, the various fabrication methods used, and the predominant characterization instruments used to evaluate particle properties (Luo & Wang, 2014). One of the areas that we will delve into is whether zein-based NPs could be used as a tool in different biomedical applications, with a specific emphasis on targeted delivery strategies (Magnabosco et al., 2023). While current research shows promising potential, gaps in understanding need to be overcome to achieve long-term stability, scalable production methods at a large scale, and extensive in vivo studies (Yuen et al., 2022). Through the critical evaluation of these elements and future research prospects, this article seeks to fill the current gap and thereby facilitate the transfer of zein-based NP technology to the clinic, where this technology will be successfully used for precision medicine approaches and targeted therapeutic interventions (Singh et al., 2024).

2. USES OF ZEIN IN DRUG THERAPY SYSTEM

Maize kernels are sources of zein, a protein that has a very unique grouping of characteristics that has surely earned its place among materials used for making targeted delivery nanoparticles (NPs) (Priyanka et al., 2019). Present in the core, their physicochemical characteristics not only make zein-based NPs these properties add to the NPs being uniquely suited for delivery applications that conventional alternatives cannot offer (Liu et al., 2023).

2.1. Biocompatibility and Biodegradability:

Zein is a biologically found protein and also the product of nature itself hence it fits fantastically well within the human's biological system (Elzoghby et al., 2017). This feature also eliminates the risk of allergic reactions or inflammatory responses, critical for drug delivery processes (Dou et al., 2020). It takes the story from being simple to being complex. When furthermore, the zein is decomposed with the aid of enzymes found in the body, the worries of long-term accumulation and toxicity are adios to such (Tortorella et al., 2021). This property promotes the digestion of zein-system of NPs after the release of the therapeutic dose they were carrying (Dunbar, 2021).

2.2.Non-Toxicity:

Zein is the "Generally Recognized as Safe" (GRAS) substance as classified by the US FDA (Anjali et al., 2023). This designated status is a proof that they have passed a high bar on safety and that the best example has been set in terms of suitability for drug delivery (Park et al., 2022). Unlike some synthetic materials, zein is actually non-toxic and free from the originating harmful effects. It may participate in the process of drug delivery more safely without producing toxicity (Jbour et al., 2019).

2.3.Film-Forming Ability:

Zein new unique property, it creates a coating layer on the nut's surface. It owns the power to bulk up into thin coats surrounding the released drugs throughout the oral intestine (Kouhi et al., 2020; Vozza, 2018). Furthermore, these wires can protect the active ingredients from breakdown in environment which is hostile by nature (Almuslem et al., 2019). Among other things, the ability to develop a film also plays a role in oral drug administration, which guarantees the whole cargo is intact at the target site until it reaches the site of action (Andretto et al., 2021).

2.4.Amphiphilic Nature:

Zein, in the form of protein, is a characteristic of strongly polarized constituents, having both hydrophobic and hydrophilic domains. Present in such a form is unique because of its ability to interact with both water-soluble and water-insoluble drugs (Tivano & Chiono, 2023). Hydrophobic segments can enclose hydrophobic drugs, the hydrophilic segments can react with water to make them able to mix with it and then disperse in all aqueous environments (Hawthorne et al., 2022). Alongside, it reduces the water solubility of these agents which enhances their ability to encapsulate drugs in larger volumes, thus making it possible to accommodate very complex molecules (Ye et al., 2018). Lipid nanoparticles containing zein protein using physical treatments has promising features like biocompatibility, biodegradability, non- toxic behavior, film forming properties and amphiphilicity, makes zein an ideal material for drug delivery (Kasaai et al., 2018; Giteru et al., 2021). Such traits provide support in drug conservation, precise delivery to targeted site and most importantly ensuring safety and effectiveness (Zhao et al., 2020).

Table 1. Properties of Zein for Drug Delivery Applications

Property	Description	Advantage in Drug Delivery
Biocompatibility & Biodegradability	Zein, being a natural protein, decomposes in the body, thereby avoiding risks associated with long-term accumulation.	Reduces the likelihood of allergic reactions, inflammation, and toxicity.
Non-Toxicity	Zein is designated as "Generally Recognized as Safe" (GRAS) by the US FDA.	Provides a safe substitute to potentially harmful synthetic materials.
Film-Forming Ability	Zein forms a protective layer around drugs during oral administration.	Shields drugs from degradation in the harsh environment of the intestine.
Amphiphilic Nature	Zein possesses both hydrophilic (water-attracting) and hydrophobic (water-repelling) domains.	Facilitates interaction with both hydrophilic and hydrophobic drugs, thereby improving encapsulation efficiency.

3. FABRICATION TECHNIQUES FOR ZEIN-BASED NANOPARTICLES

The distinct features of zein, which may be mainly attributed to its amphiphilicity and ability to form film, produce it eligible to diverse fabrication techniques in nano-size particles (NPs) (Zhang et al., 2020). The efficiency varies with the technique, which in turn affects physicochemical attributes of the thus produced NPs, i.e., size, structure, and drug loading level (Mitchell et al., 2021). Here, we explore some of the most commonly employed fabrication methods for zein-based NPs:

3.1.Nanoprecipitation:

Underlying Principle: This method, which involves an ultrafast diffusion of zein solution into water under continuous stirring or ultra-sonication, serves as the fundamental tool. The cationic polarity fluctuation will lead to the self-assembly of the zein molecules and thus nanoparticles will be made (Zeng, 2021; Delavault et al., 2021).

Factors Influencing NP Characteristics: The choice concentration of zein, type and the ratio of solvents being used, stirring speed and sonication settings is what will have the greatest effect on the size and structure of the NPs obtained (Elmizadeh et al., 2024). High levels of zein may result in larger NPs; however, solvent ratio has a significant bearing on hydrophilicity, drug loading and other NMs' properties (Zeinali et al., 2020).

Advantages: Nanoprecipitation is a versatile, rapid, uncomplicated, and large-scale production method because of its ease of use. It provides for well manipulation of the NP diameter and the loading capability (Rivas et al., 2017).

Disadvantages: This way can generate particles with varying sizes, even the aggregation of NPs can be possible (Shrestha et al., 2020). To add to this, further purification might be required for the organic solutions.

3.2.Emulsion Techniques:

Underlying Principle: It is in this class that a diverse range of methods are used for creating oil-in-water (o/w)/ water-in-oil (w/o) emulsion by taking zein solution as a source of either the oil or aqueous phase (Kumar et al., 2022). For further augmentation x component of zein gets added to give the solvent evaporation or non-solvent followed by NPs self-assembly (Liu et al., 2023).

Types of Emulsion Techniques:

Solvent Evaporation: In this place, an oil in water (o/w) emulsion is formed where zein is located in a non-water (organic) phase. The solvent is then boiled out and the zein solution becomes a precipitate, hence a nanoparticle formation is achieved (Tian, 2020).

Nano droplet Emulsification: This method does so by manufacturing and utilizing microfluidic devices which ultimately help to generate uniformly sized drops of zein dispersion in a non-solvent. Solid stage initiates and the fume are transformed to a droplet which immediately solidifies to form NPs (Logesh et al., 2021; Rayees et al., 2024).

Factors Influencing NP Characteristics: The form of the emulsion, the ratio of the phases, and the homogenization speed have a paramount impact upon the NP size and architecture (Rabanel et al., 2019). Apart from that, organoleptic properties of solvents largely affect drug loading and release capabilities (Kouhi et al., 2020).

Advantages: Emulsification methods provide good dispersion properties that allow to make a product with different characteristics, such as the formation of two phase systems and the opportunity to fill the drug by hydrophilic and hydrophobic components (encapsulation) (Ding et al., 2019). This technique of Nano droplets' emulsification allows to create NPs with very homogeneous and well-differentiated structures (Stintz et al., 2022).

Disadvantages: Disposing the organic solvents remains a big issue, while the process is more complicated than the nanoprecipitation method (Chen et al., 2023).

3.3.Electro spraying:

Underlying Principle: In this method we use high potential to create aerosol – binary system of the fine drops. When those water pigeons move in an electric area, solvent evaporation and solidification happen and they become NPs (Zhou et al., 2021).

Factors Influencing NP Characteristics: The amount of applied voltage, the flow rate of the zein solution and the distance between the nozzle and collector all play an important role in choosing between large or small nanoparticle sizes and particle conformation (Silva et al., 2021). There are moreover certain solvents and additives that can interfere with the way the process operates.

Advantages: Electro spraying leads to uniform-sized HPs with a high encapsulation efficiency for the targeted drug delivery to hydrophilic as well as hydrophobic regions (Pawar et al., 2018). This method is usually solvent-free and from it takes control of the particle morphology. This means that this is simplest way for synthesis of inorganic polymer with good control of the particle shape (Li et al., 2019).

Disadvantages: The setup be expensive and the reaction parameters need precise optimisation for the good characteristics of NPs (Khan et al., 2019).

3.4.Coacervation:

Underlying Principle: The self-assembly mechanism utilized, in this case, is the phase separation of zein solution when a coacervating agent, such as sals or a pH change, is added (Roy, 2024). By combining the zein particles at a vapor or aqueous phase, a dense liquid phase will be formed which can then be subjected to various treatment processes to produce nanoparticles (Kasaai, 2017).

Factors Influencing NP Characteristics: It is the type and concentration of the creating fans, pH, ionic strengths, and processing steps which immensely influence the size and mass pattern of the gentamiens (Atugoda et al., 2020).

Advantages: The technique of coacervation being a simple and a less harmful method ensures that the encapsulation of the sensitive biomolecules is done. However, it is normally a solvent-less method (Satapathy et al., 2021).

Disadvantages: Control over the size and shape of the NPs is marginal as it is the major differentiating component from the other techniques. Moreover, formation of NP from the coacervates may be diluted by the coprocessing steps (Wang et al., 2018).

The manufacture method chosen for zein-based nanoparticles depend greatly on the desired needs, which includes encapsulation of drugs, the characteristics of these nanoparticle and the scalability requirements (Tortorella et al., 2021; Tivano et al., 2023). Realizing that no method seems to be more perfect than others, researchers can make the fabrication method more adaptable to the desired NP properties relative to the specific drug delivery applications in question (Procopio et al., 2022).

This image shows the scale of a nanometer compared to other objects. It can help you understand how small zein-based nanoparticles are.

4. CHARACTERIZATION TECHNIQUES FOR ZEIN-BASED NPS

We have identified zein protein, which is obtained from corn as our latest materials for nano-fabrication. Such nanoparticles, that are degradable, are biocompatible as well as amphiphilic in nature, showcase a high level of great diversity in various fields such as drug delivery, bio imaging and tissue engineering (Meher et al., 2020). Though it is necessary to know about their qualities and behavior for their proper functioning, partners need to have some distance as well (Widdus, 2017). Characters are what art is made of, and the longer they are believable and authentic, the stronger the connection the audience will feel (Moustakas et al., 2020). By these techniques, researchers are able to do a visualization of zein-based nanoparticles in them which includes all the aspects. So, adjusting zein nanoparticles for usage in specific areas can be easily predicted.

4.1.Unveiling the Size and Shape:

Dynamic Light Scattering (DLS): The principle of this method does not involve in physical messing with nanoparticle and measures scattered photons to obtain calculations the size distribution (polydispersity index) and mean size of particles in suspension (Carvalho et al., 2018). DLS analyzes the size distribution of nanoparticles very fast and it indicates the typical size of a large number of those particles within the sample (Caputo et al., 2019).

Transmission Electron Microscopy (TEM): TEM which has a capability to provide high definition images enables visual inspection of the individual nanoparticles with regard to their shapes and dimensions (Song et al., 2019). Through studying the pictures that have been captured, scientists will then be able to assess the precise size and shape (round, oval,) of the nanoparticles.

Atomic Force Microscopy (AFM): AFM, in addition to rendering the whole topography (shape) similarly to the bottom graphical images, can also observe the surface roughness, and the mechanical properties of single nanoparticle (Krieg et al., 2019). Furthermore, the comprehensive study of how zein nanoparticles will interact when they are exposed to the environment is made possible.

4.2.Decoding the Surface Charge:

Zeta Potential Measurement: The zeta potential thereby defined deals nor grains the electric charge in dynamic equilibrium near the surface of nanoparticle in a liquid medium. This principle governs, among others, the dispersivity, the pairing, and the organic penetration (Rusheng et al., 2022). Electrophoresis is the most commonly used technique for the evaluation of zeta potential; the principle of devices using this technique is based on this parameter (Sarmiento et al., 2018).

Then, high zeta potential with positive or negative value indicates superior colloidal stability, thus particle suspensions are not aggregating.

4.3.Unveiling the Inner Workings:

Fourier-Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy examines the chemical constituency of the formed nanoparticles by discovering functional groups that contain zein protein (Badgujar & Kumar, 2021). This gives scientists a definitive notion on whether certain gene expressions and cargo have been successfully delivered to the nucleus.

Differential Scanning Calorimetry (DSC): DSC uses the nanoparticle's thermal characteristics to reveal its melting point temperature, glass transition temperature, and general thermal stability (Han et al., 2020). Having this understanding, applications, where temperature influence is important for instance in drug release control or drug delivery, are facilitated.

X-ray Diffraction (XRD): XRD mainly sheds light on the crystalline nature of zein nanoparticles constituting them. The way how not just the native crystalline form of zein, but also how zein may have changed its arrangement with respect to processing methods are examined with this approach (Wang et al., 2023).

Encapsulation Efficiency: For zein nanoparticles fabricated to accommodate drugs and their delivery content, the quantification of such cargo molecule is central. Concentrations of the cargo in the supernatant can be determined by UV-Vis spectroscopy or HPLC (Picos et al., 2023). These concentrations can then be compared to the initial amount incorporated into the particle to assess encapsulation efficiency. This determines if the total content of cargo in the nanoparticles has been trapped or not and helps researchers calculate and track the percentage of cargo successfully encapsulated in the nanoparticles.

In Vitro and in Vivo Studies: This information is important and may guide researchers and entrepreneurs in understanding the structural elements of zein NPs responsible for desired mechanisms of action in the transport processes across cell membranes (Saeed et al., 2021). Health in vitro assays which can evaluate uptake into cells, cellular toxicity and therapeutic effect on cells as possible. In the case of animal model studies in vivo we observe that Zein-based nanoparticles transport to various organs, show their activity and can induce side effects mostly in the liver (Asrorov et al., 2023).

Most notably, characterization methods are the key to the mystery of zein-based nanoparticles lay in this. With such techniques as Nano tracking and nanoparticle profiling, researchers can determine the size, shape, surface charge, internal structure, and cargo encapsulation efficiency to give the whole image. This information is critical for the formation of zein-based nanoparticles that will punitively be applied in areas like drug delivery, bio imaging and other fascinating fields. It will also be the start of some great advancements in nanotechnology.

5. BIOMEDICAL APPLICATIONS OF ZEIN-BASED NANOPARTICLES IN DRUG DELIVERY

The field of medication delivery is always in the dynamism of improving the drugs that have both high effectiveness and safety. In this process, frequently even natural polymers like zein are becoming promising active ingredients for designing drug delivery systems which have not been used so far (George et al., 2019; Berardi et al., 2018). Zein, the protein from corn grain, is very special, which possess amazing ability to be employed in the delivery of therapeutic agents. This article is all about the power of zein-based nanoparticles in the biomedical realm where they are just much anticipated for drug delivery.

5.1. Zein: Problems encountered in medical applications.

Along with problems of lacking stability, solubility, and negative side effects, the limitations of conventional drug delivery methods are one of the issues that must be solved. Zein may succeed by his powerlessness over these obstacles (Bhalerao et al., 2020). Here's why zein is a promising material for drug delivery: Here's why zein is a promising material for drug delivery:

Biodegradability: The protein zein from the corn plant is just a natural example that is generally digested easily by the human body without giving a chance for accumulation or toxicity (Jaski et al., 2022).

Biocompatibility: Made initially from food, zein has few adverse immunologic effects thus making it a safe substance to be used within the human body (Garavand et al., 2022).

Amphiphilic Nature: So zein is a molecular chain displaying both hydrophilic (water-loving) and hydrophobic (water-repelling) regions. Such a property provides IDE with this unique capacity to interact with both water soluble and water insoluble drugs and as well offers versatility in drug encapsulation (Sabir et al., 2019).

Controlled Release: Zein Nano Articulation can be designed to the release of their cargo in a controlled manner. This is realized by taking into account factors such as particle size, and surface modification which result to making the drug available for the desired period of treatment (Chadha et al., 2022).

The Application of Zein-Based Nanoparticles as a Carrier in Drug Targeting.

Due to its particular qualities Zein offers an attractive scope of wide opportunities for medications supply. Here are some key areas of exploration: Here are some key areas of exploration:

Enhanced Drug Solubility: The presence of many strong substances have poor solubility in water because of that the drugs get absorbed very slowly and therefore are not very useful. Drugs that have low intestinal solubility and bioavailability can be entrapped by the Zein nanoparticles which can enhance their solubility and bioavailability (Zhang et al., 2018).

Targeted Drug Delivery: Nanoparticles designed from zein can be manipulated to have a certain ligand prone to side-specific or tissue-specific targets, the method of which completely depends on researchers. This approach can dramatically reduce the occurrence of undesirable reactions and improve the effectiveness of therapeutic drugs (Tran et al., 2022).

Protection of Drugs from Degradation: The drugs might be degraded during its transmission to the site where it is supposed to take effect. The shielding of drugs by zein nanoparticles from the environmental elements results in net increase in drug stability and delivery to their respective region of activity (Prajapati et al., 2019).

6. ZEIN-BASED NANOPARTICLES IN CANCER THERAPY

Cancer, an insidious threat planting the seeds of millions of deaths yearly, warrants novel therapeutic approaches. Nanoparticles are one of the strategies which is gaining popularity day by day because of their potential to direct medicines to the specific location. Zein, protein extracted from corn, is front of the pack here. The advantages of zein as a nanoparticle meant for targeted cancer therapy comes out superior to other forms of treatments (Singh et al., 2023).

6.1. Zein: A Powerful Arrow in the Fight Against Cancer

Zein, a protamine protein present in corn alone, offers a unique process of self-assembly, which is difficult to master. This indicates that when zein strikes a specific environment it may naturally adopt the form of nanoparticles (Pinto et al., 2022). These zein-based nanoparticles (ZNPs) boast several characteristics that make them ideal candidates for cancer drug delivery: These zein-based nanoparticles (ZNPs) boast several characteristics that make them ideal candidates for cancer drug delivery:

Biodegradability and Biocompatibility: In contrast to some other synthetic materials, this Zein has the ability to be easily eliminated by our body, hence it avoiding any side effects or adverse reactions (Pérez et al., 2020). Besides, the absence of immune rejection risk, due to its natural origin, is another feature of it.

Enhanced Drug Solubility: Thus, many [strong] anti-cancer drugs have difficulty in water solubility which hinder effectiveness. ZNPs can be an effective encapsulate of those drugs which increases their solubility and bioavailability therefore improves the selective delivery of those drugs which carry out the target treatment (Gandhi et al., 2021).

Controlled Drug Release: Using Zein nanoparticles, we can develop a system that can be designed to give the same response at certain signals like pH change or enzymatic activity. It is designed to degage the drug inside the tumor microenvironment, thus supporting the drug concentration to normal areas of body (Kaushik et al., 2020).

Potential for Targeted Delivery: Scientists are engaged in studies to see how the ZNPs may be functionalized with ligands that determine activation of the receptors present on cancer cells. Such a selective type of treatment would very likely diminish the chance of harm of the normal cells and at the same time enhance the outcome of the treatment applied to a tumor (Anjum et al., 2021).

7. ZEIN-BASED NANOPARTICLES IN INFECTIOUS DISEASE TREATMENT

The fight for the well-being against the contagious and newly coming viruses will never be over, as the resistance they bring along will always remain to menace the unfortunate of the world. While researchers probe the effectiveness of different drug systems, they also offer better treatment efficacy so that the infected areas will be targeted precisely. Nontoxic nanoscale zein nanoparticles have emerged as an effective weapon in anti-infective armory and this delivery system provides improved advantages compared to what is created by currently used methods (Campos et al., 2024).

Zein, a material extracted from corn, is well-endowed with the features that required for such a development. It is non-toxic in general as it doesn't do any damage to the body and degrades biologically in a manner that it gets broken down in the body after their purpose is served. zein also reveals amphiphilic properties, having hydrophilic and hydrophobic regions. This feature enables it to auto-arrange itself into nanoparticles encapsulating medicine in its core with the absence of external environments influence (Omosebi et al., 2018).

Another major advantage of zein-based nanoparticles is their ability to select the specific impact points in the human body and deliver the drug to those spots. Typical antibiotics are frequently active both on good and bad bacteria; they do not differentiate between them as the natural antibiotics do. Those symptoms can be due to the disruption of the gastrointestinal microbiota and the development of antibiotic resistance (Hassan et al., 2022). Nanoparticle of Zein has the ability to control at what place the drug will be release. For example, researchers are countering by designing zein nanoparticles to disintegrate in a response to the distinct enzymatic conditions of the colon intestine. The local action facilitates the fighting against pathogens that are residing there, by limiting the surrounding colonies which will in turn minimizing the side effects of the antagonistic consequences on gut flora.

The degradability is also positives sharp of Zein. Contrary to some artificial polymer used in the development of synthetic nanoparticles, zein doesn't remain in the body unabsorbed and the mass of residual elements could become a burden to the organism (Leyva et al., 2021). It therefore has a higher degree of fidelity from existing genetic disorders in the patients, which makes it an option for heavy load usage in long term treatment regimens. The current landscape of infectious disease treatment highlights several areas where zein-based nanoparticles can be particularly beneficial: The current landscape of infectious disease treatment highlights several areas where zein-based nanoparticles can be particularly beneficial:

Gastrointestinal Infections: The use of zein nanoparticles aids in formulating the drugs for oral administration as it helps the enclosed drugs to withstand the harsh stomach acids nor adults (Cote et al., 2021). Specificity of this technique brings a hope for treatment of infections by bacteria like Bactericides fragile and the species which is associated with peptic ulcers- Helicobacter pylori.

Fungal Infections: In terms of some fungal infections, the colon especially, are a distinct problem in which medicated drug administration to appropriate area is a hard task. Nanoparticles of zein that are specifically designed for the colon can be a breakthrough, contending with treatment inefficacy caused by these infections (Albogamy et al., 2023; Cote et al., 2021).

Antimicrobial Resistance: The emergence of antibiotic-resistant microorganisms urges new treatment methods for such infections. Zein nanoparticles can be loaded with updated or current antibiotics; this phenomenon might improve the antimicrobial agent's efficacy and safeguard it against resistance strategies (Dupuis et al., 2022).

Parasitic Infections: The number of the poor who are parasitically infected comprises many people in the Globe. Zinc nanoparticles can be used as a drug carrier to targeted infections location, thereby enhancing the treatment outcomes with reduced side effects. The scientific studies concerning zein- based nanoparticles for infectious disease treatment is yet to be fully developed. But, the returns are good at the moment (Madkhali et al., 2023).

8. ZEIN-BASED NANOPARTICLES FOR TARGETED DRUG DELIVERY

The design of drugs has become a constantly improving area with researchers investigating the best methodologies to optimize safety and sufficient utilization of biopharmaceuticals. With cost-effective and efficient characterization protocols as the bedrock, zein-based nanoparticles have paved the way for the introduction of targeted drug delivery as a promising platform (Mishra et al., 2018). Zein, a protein obtained from corn, is remarkable by the fact that it has got its own unique properties that make it very applicable within the scope of this particular scientific goal (Uan et al., 2018).

The core reason infecting Zein's application as a drug deliverer is rooted in its innate variability. Therefore, it is a natural, biocompatible, and bio degradative polymer. This simple means that there is no much toxicity to the body and the carrier breaks down the tongue after delivering the desired dose (George et al., 2019). In contrast to saw-synthetic-polymers used in some nanoparticles, zein is not considered to be the cause of long-term environmental problems. Concerning, zein is characterized by the unique fact that it includes amphiphilic properties. In simple language it has the ability to hold hydrophobicity and hydrophilicity at the same time within its structure (Tortorella et al., 2021). This tendency of zein to segregate into nanoparticles creates a hollow core layer encapsulated by the protein shell. Hydrophobic core can work as an umbrella over the drug encapsulating it efficiently while the hydrophilic shell makes the interaction with water based environment such as the bloodstream easy (Hawthorne et al., 2022).

9. THE UPCOMING HURDLES AND EXPECTATIONS FOR ZEIN-BASED NANOPARTICLES

The key issues in moving decreased from the zein-based nanoparticles into the clinical practice for the targeting drug delivery should be solved out. Here's a closer look at these hurdles and promising future directions: Here's a closer look at these hurdles and promising future directions:

9.1. Challenges:

Optimizing Drug Loading and Targeting Efficiency: Zein is quite a good choice as a material for controlled release especially due to its biological origin. However, scientists still need to work on optimizing the drug loading and controlled release (Abdelsalam et al., 2021). This is achieved by adjusting nanoparticle structure and surface properties e.g. surface modifications to maximize the effectiveness of the drug release system and limit the rate of release at the target site. Moreover, apart from creating the targeting techniques for the specific tissues and cells the goal of limiting the side effects and increasing the treatment proficiency still is a matter of concern for the researchers.

Large-Scale Production with Consistent Quality: There are concerns about instability in the production of zein used in pharmaceutical treatments as no standards exist. Coming out with low-cost production routes of zein that have be maintenance of physicochemical parameters is key. Stability further serves the definite production of nanoparticles for therapeutic applications that demonstrate predictable action (Sun et al., 2023).

Addressing Blood Accumulation and Clearance: Despite zein not being biodegradable, this environmental problem has to be regarded as very onerous from the stand point of the users of nano technology. Nanoparticle size and surface properties might be fine-tuned, so they are able pass immunological defense and exit in circulation until reaching the target site (Gupta et al., 2022).

Extensive in Vivo Studies: The in vitro trials have been able to deliver but in living organisms, the complete in vivo evaluation of zein-based nanoparticles' safety and efficiency is a necessity (Reboredo et al., 2021). This means that you are determining potential long-term toxicity profile in animal models, animals carrying bio distribution profiles, and also evaluating therapeutic effects.

9.2. Future Perspectives:

Advanced Characterization Techniques: In addition to nanoparticle tracking analysis and nanoparticle profiling which can further offer more detailed information about zein nanoparticles activity in biological systems, advanced characterization techniques will play a key role in this development (Shakiba et al., 2020). This can be used in collaborating with researchers to make sure that the drug delivery mechanism design would be effective in the targeted drug delivery.

Combination with Other Biocompatible Polymers: The blending of zein with other chemical biosafety polymers can provide an array of new opportunities. Thus, targeting nanoparticle stability might be preferred to maximize the loading capacity and create more complex delivery systems with desired functionality for particular uses (Makvandi et al., 2021).

Exploration in New Therapeutic Areas: Nanoparticles derived from zein are being studied today for many different roles in drug delivery aside from conventional drug delivery (Abdelsalam et al., 2021). The people who are practicing gene therapy, delivery of biomolecules such as proteins and enzymes and even the imaging techniques, hold great promise for the future research in the direction of personalized medicine.

Overcoming Manufacturing Challenges: Scale-up methods for zein purification and nanoparticle production that are also cost effective will be supporting factors in the transition from research to a clinical setting (Tivano & Chiono, 2023). Solving these challenges will be a way towards the extension of nanoparticles use in applications that are therapeutic and so on.

CONCLUSION

The idea of Zein based nanoparticles indeed presents an opportunity for revolutionizing targeted drug delivery. The features of their biodegradability, biocompatibility, surface activity and controlled delivery of drugs make them suitable for several medical therapies. Characterization techniques have been a crucial aspect in the study of their various properties, and that has greatly improved their design. Nonetheless, challenges are still apparent in getting efficient drug loading, the targeting of specific targets, and the standardized therapeutic production that is desired. Long term in vivo studies in animals is also required for translation to human and clinical studies. Next innovations in designing polymers with improved characterizations, exploring of smart and combination polymers, and investigations in new therapeutic areas will lead to the innovative era in medicine. Overcoming the hurdles of production will play a critical role in more general clinical usage. Such nanoparticles, still in development, can propel the way we treat diseases to safer and more effective drugs by delivering the drugs with higher concentrations in targeted area.

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