"NANOTECHNOLOGY IN DRUG DELIVERY: RECENT DEVELOPMENTS AND THERAPEUTIC APPLICATION"

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ABSTRACT –

Drug delivery methods have been completely transformed by nanotechnology, which provides improved therapeutic effectiveness, controlled release, and precise targeting. This thorough analysis looks at the most recent uses of nanotechnology in medication delivery. An introduction to nanocarriers, including liposomes, polymeric nanoparticles and dendrimers is followed by an explanation of their distinctive characteristics. The study focuses on how these nanocarriers, which encapsulate a variety of medications including biologics, gene therapies, and chemotherapeutics, allow for site-specific delivery, overcome biological barriers, and lower systemic toxicity. In addition, the importance of nanotechnology in personalized medicine and its potential for overcoming medication delivery difficulties are highlighted. Furthermore, regulatory issues, obstacles, and future possibilities in the sector are discuss, highlighting the importance of additional study to maximize clinical translation. The goal of the article is to give the complete summary of recent breakthroughs & possible usages of nanotechnology on drug delivery systems, hence encouraging continuous improvements and innovations in this promising sector.

KEY WORDS –

Nanoparticles, Dendrimers, Micelles, Liposomes, Niosome, Phytosome, Transfersome, Targeted drug delivery, Bioavailability, Controlled release, Biocompatibility, Fullerenes, Blood brain barrier, Tackling urological disease, Oligonucleotide drug delivery.

INTRODUCTION -

The word Nanotechnology was originated via the Greek word "Nanos" (dwarf or incredibly little) & “logos” means study or science(1) which is invented by the scientist N. Taniguchi in the year 1974.(2) Thus the Nanotechnology is the study of tiny things or nanoparticles, which have 1 to 100 nm in size. 1 nanometer is equal to 10^{-9} or 1 billionth of a meter(3). Nanotechnology is generally initiate in USA.(4) And it is amongst the best auspicious technologies of the 21st century.(5) So the Nanotechnology is an engineering, scientific, and artistic technique of controlling or manipulating the material at nanoscale and capability to transform the nanoscience theory to useful applications or practical by the design, creation, synthesis and production.(1) And it is a relatively new technology capable of creating engineering beneficial substances, mechanisms, and gadgets on the nanoscale.(4)Nanotechnology is a creative scientific authority that established the groundwork for innovative and creative methods in a wide range of medical science fields. According to the United States National Science and Technology Council, nanotechnology is a subject that is closely related to seeing, evaluating, and working with materials at the atomic, molecular, and supramolecular levels. These field of medicine determine to nanotechnology application in existence accepted in nanoparticle are utilize to supply drug.(6)

The recent nanotechnology revolution has had a significant impact on several scientific disciplines, including chemistry, biology, and engineering.(7) Field nanotechnologies has been undergoing a huge development in the recent few years. It is extremely important to the advancement of many scientific disciplines, like fiber optic communication network, chemical engineering, aerospace science or research, robotics devices, electronics and in material science.(8) Recently in the field of therapy & diagnosis of various disease the nanotechnology gives more contribution and it has a significant part in the production of biocompatible material & surface, analytics and diagnostics, local transport of active substance, and the production of various active pharmaceutical ingredients(API).(9)

Nanoparticles are extremely important in the nanotechnology, As per definition from (NNI) national nanotechnology initiative. Theses are the granular solid colloidal particles or small in particle size from the range of 1nm to 100 nm. They are consist of macromolecular material in which the active pharmaceutical ingredients (API) are dissolved, entrapped, or attach to a nanoparticle model (10) Nanoparticles are considerable technology activity, in which they are the successful branch, between the bulk material and atomic or molecular structure. The primary cause of nanoparticles is the substance's huge area of the surface that are improved by small bulk material.(11) Nanoparticles are careful delivery system in a variation of disease. The FDA's approval of the manufacturing of nanoparticle drugs (12). Main characteristics among the nanoparticle system are size distribution and particle size (13) and nanoparticles holds the large surface area that gives to significant biological activity per mass.(14) There are several kinds of nanoparticles, including-

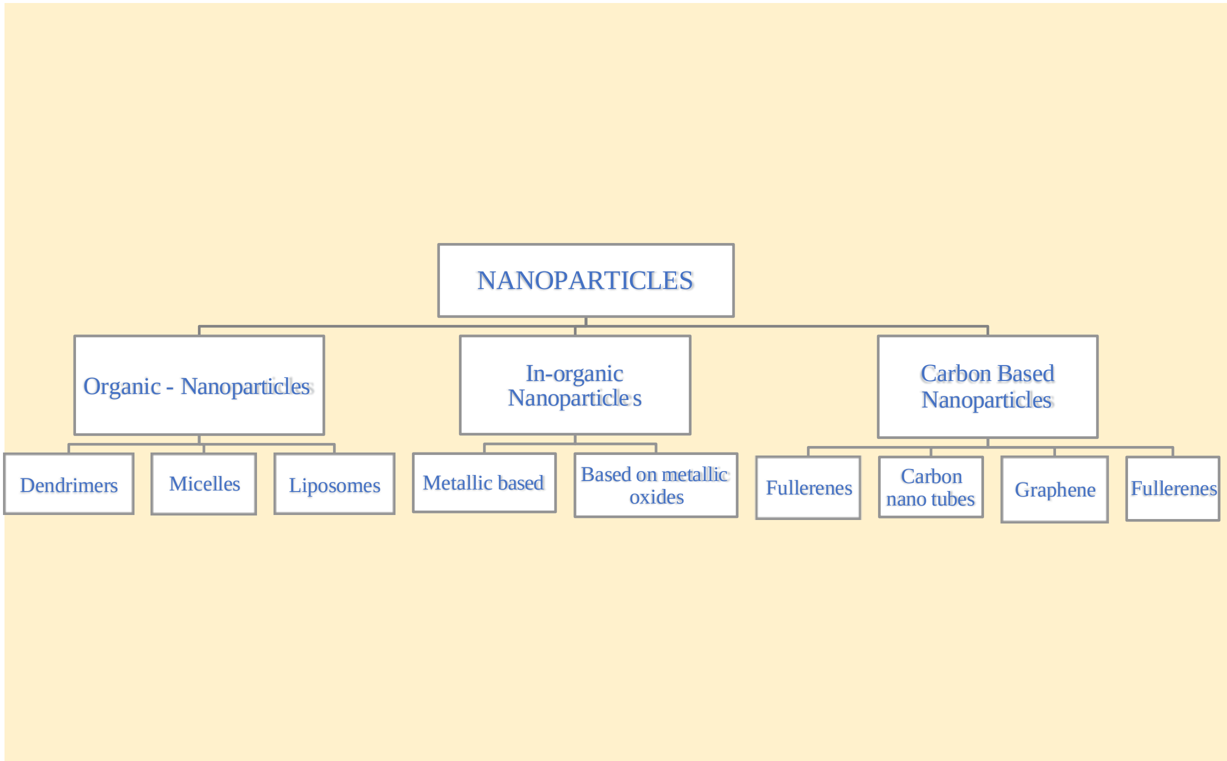

Figure :- Categorization of Nanomaterials

UTILIZATION OF NANOTECHNOLOGY IN DRUG DELIVERY SYSTEM :-

The term “distribution of drug” "drug delivery" or describes the strategies, compositions, production methods, and technologies used in the distribution of an active biopharmaceutical component or chemical to its intended therapeutic location. (15) Nanotechnology for drug delivery is concerned with the whole spectrum of nanosized materials which has certain size depending properties of the biological and biomedical significance or relevance. And this may involved in the development or enhancement of the intracellular delivery and subcellular distribution.(16)

The drug delivery system is a method of transporting or supplying of the medicines to the receptive into a way which may enhance the concentration of the medications into a some parts of the body relative to other.(17) Different types of medication delivery systems are classed based on how they are administered. Modern drug delivery methods are paying more attention to NDDS like target drug distribution & DDCs, in addition to supplementary conventional methods like orally, via transdermal, injectable, implants, inhalation, suppositories, otic, as well as ophthalmic forms of dosage.(18)

Drug device combination is a method for the providing clear benefit, since the last few years, the drug device combination system attracts the increasing awareness from the health care & pharmaceutical industries. For example insulin pump etc.(19) Drug distribution for the target are a method of drug aggregation at the specific target site that is not based upon the routes of remedy administrations.(20) The main purpose of the drug distribution strategy is to provide the medication at the precise concentration in the appropriate place for the accepted session of time. To drug characteristics be different considerable of chemical composition, molecular size, hydrophilicity, & protein binding, the needed in characteristic in value of highly complex.(21)

To the expensive of smart nanotechnology is based on fixed drug delivery system in possible submission for the comfort ideal level of medication at the intended location.(22) The novel drug delivery system (NDDS) is an advanced and modern delivery system of the drug into the patients which prevents the several problems of the traditional drug delivery system such as instability, high dose and less bioavailability, variations of plasma drug level, first pass metabolism or effect, and fast release of the medicinal substances through the execution, protection, adherence with the patients, and product’s shelf life.

There are several varieties of innovative medication delivery systems, including -

- Liposomal drug delivery
- Niosomal drug delivery
- Phytosomal drug delivery
- Transfersomal drug delivery (23)

❖ LIPOSOMAL DRUG DELIVERY –

These are small molecules and made up of material of cell membrane. And liposomes are mainly filled with chemical compounds or medications which are generally used to deliver medications for different kinds of diseases such as cancer , kidney disease, CNS disease etc. Dr. Alec. D. Bangham FRS, a British haematologist, created the word liposome in 1961 at the Babraham Institute.(24) According to their structural characteristics, liposomes come in a variety of forms which are (tab.1)(25) –

Type of vesicle	Acronym	Number of lipid bi- layer	Diameter size
Large unilamellar vesicle	LUV	1	>100 nm
Medium unilamellar vesicle	MUV	1	>100 nm
Small unilamellar vesicle	SUV	1	20-100 nm
Unilamellar vesicle	UV	1	All size range
Giant unilamellar vesicle	GUV	1	>1 µm
Multivesicular vesicles	MV	Multicompartmental structure	>1µm
Multilamellar vesicle	MLV	5 to 25	>0.5
Oligolamellar vesicle	OLV	Approximately 5	0.1 to 1 µm

Table -1

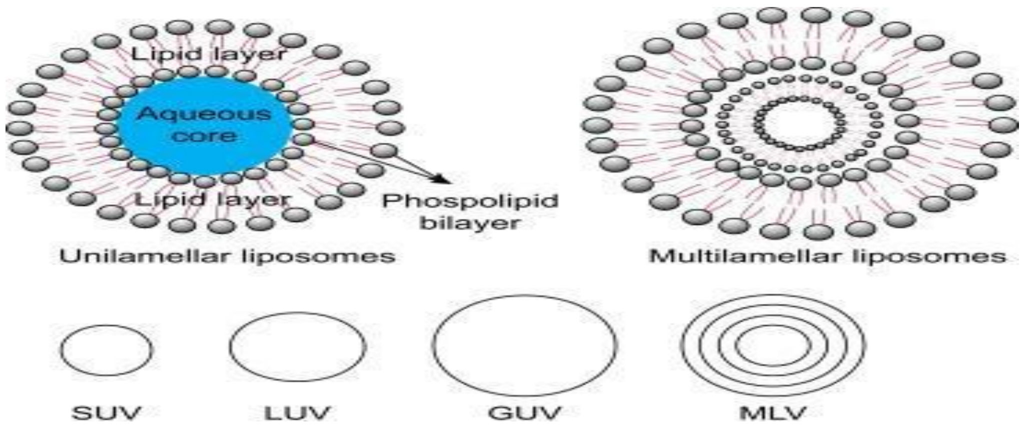

Figure :- Structure of liposomes(26)

❖ NIOSOMAL DRUG DELIVERY -

A niosome is a liposome made of nonionic surfactants. Niosomes are mostly generated by the addition of cholesterol as a component of various excipients may be utilized as well. Niosome have a greater capacity to penetrate than earlier emulsion formulations.(27) There are several type of niosome which are (Tab. 2).(28)

Vesicle type	Abbreviation	No. of lipid bi-layer	Diameter size
Multi lamellar vesicles	MLV	>1	0.5-10 µm
Large unilamellar vesicles	LUV	>1	100 to 3000 nm
Small unilamellar vesicles	SUV	>1	10 to 100 nm

Table -2

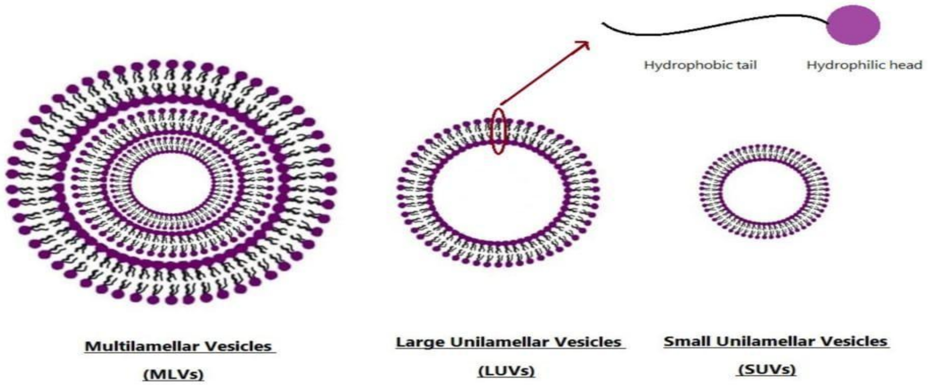

Figure :- structure of Niosomes (29)

❖ PHYTOSOMAL DRUG DELIVERY –

The word "Phyto" denotes plant, and "Some" implies similar to a cell. Phytosomes are colloidal dispersion drug delivery mechanism where by plant-derived botanical compounds surrounding and are bound with lipids (a minimum of one phytoconstituent particle associated with the minimum of single phospholipid atom).(30)

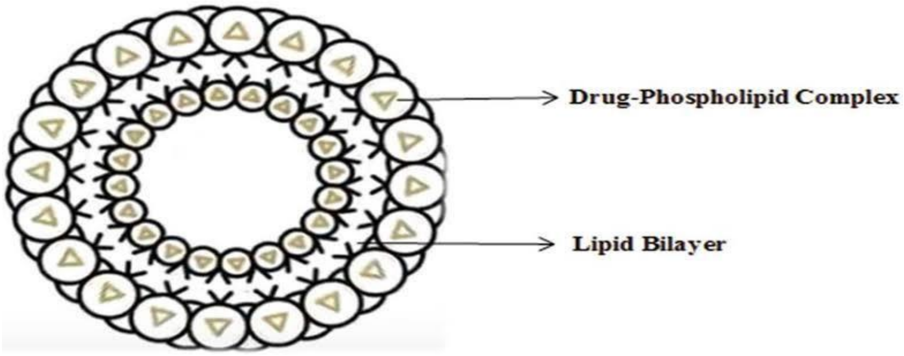

Figure:- structure of phytosome(31)

❖ TRANSFERSOMAL DRUG DELIVERY –

Transfersome is a trade name used by the German business IDEA AG for the purpose of reference to this patented medication distribution technique. Transfersome carrier is a kind of synthetic vesicles that may be used for focused and controlled administration of medication since it functions similarly to cellular vesicles as well as a cells in exo-cytosis.(32)

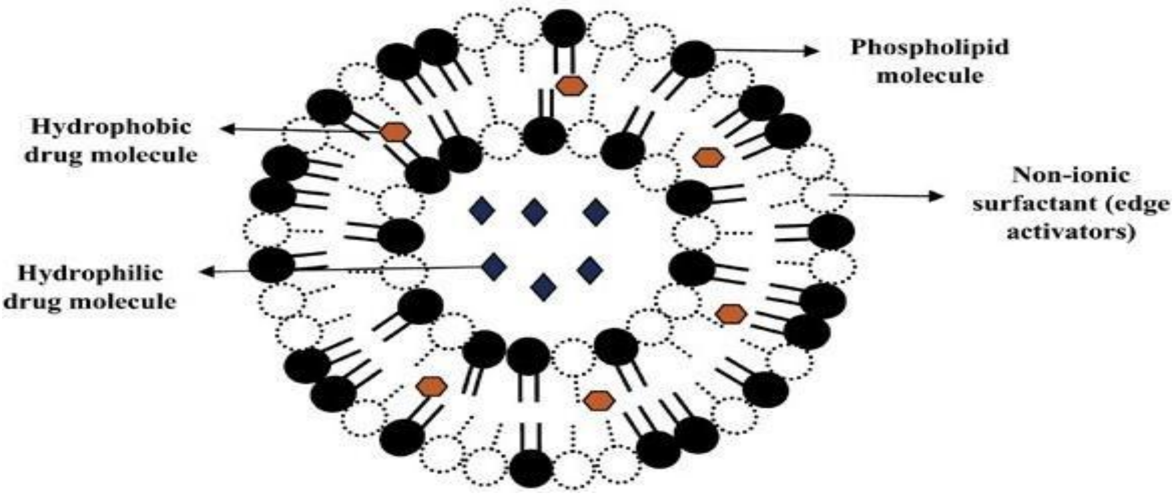

Figure:- structure of transfersomes (33)

RECENT APPLICATION & ADVANTAGES OF NANOTECHNOLOGY IN DRUG DELIVERY –

1. APPLICATION OF NANOTECHNOLOGY IN CEREBRAL ENDOTHELIUM -

The brain, A vital & complex organ, requires protection from external harm. Brain tumors like glioblastomas are challenging to treat due to the blood-brain barrier (BBB)**,** that blocks most chemotherapy drugs. Nanoparticles (NPs) offer a promising solution. These nanocarriers can deliver drugs specifically to tumor cells, aid in tumor diagnosis and surgical visualization (helping distinguish cancerous from healthy tissue), and bypass the BBB using various mechanisms and ligands. Common nanocarriers include gold, silica, carbon nanotubes, dendrimers, and polymeric nanoparticles.

NPs also act as effective imaging agents by targeting cancerous cells and delivering contrast substances (like gadolinium-based compounds) for improved MRI imaging of gliomas. This theranostic approach allows for simultaneous treatment and imaging of brain tumors, minimizing side effects by concentrating drugs at the tumor site. NPs can cross the BBB through mechanisms like penetrating endothelial cell junctions, endocytosis, transcytosis, and receptor-mediated transport, with lipid nanoparticles being particularly effective due to their lipophilic nature.(34,35,36,37,38)

2. UTILIZING NANOTECHNOLOGY TO TARGET ANTIBODIES –

Since the 1970s discovery of mouse hybridoma technology, monoclonal antibodies (mAbs) have revolutionized medicine, becoming a leading therapeutic modality. Initially used therapeutically (like muromonab CD3), their applications have expanded to include diagnostics and drug delivery, particularly with nanoparticles.

mAbs and their fragments act as targeting receptors for drugs, delivering nanomedicines to specific sites, and as diagnostic tools when labeled. They're frequently used to create nanoparticles (polymeric, SPION, phospholipid-based) with specific ligands for diseases like lung cancer, improving therapeutic effectiveness and facilitating regulated medication release by boosting drug accumulation at target areas. Nucleic acids are also increasingly being used in cancer detection and treatment. One interesting field is creating new mAb-conjugated nanoparticles for targeted medication delivery in pulmonary carcinoma.(39,40,41,)

3. APPLICATION OF NANOTECHNOLOGY IN PULMONARY DISEASE-

Lung diseases are a major global health concern, with fatalities projected to rise. Early and accurate diagnosis is crucial for effective management, and nanobased biosensors are proving invaluable for rapid identification of various pulmonary conditions, including asthma, lung cancers, and infections. During epidemics, these sensors facilitate precise contact tracing and widespread testing. A key concept in nanomedicine for lung treatment is active targeting, where nanoparticles (NPs) are designed to deliver drugs specifically to diseased areas. This precision medicine approach reduces drug experience to healthy tissues, minimizing side effects & requiring lower doses.

NPs can be inhaled, diffuse through airways, and deposit in air sacs, interacting with lung cells. Their properties (size, shape, surface charge, moisture absorption) are vital for effective interaction with the body and for targeted delivery, which in turn limits side effects.

NPs achieve targeting through two main methods: passive targeting leverages the leaky blood vessels and impaired drainage often found in tumors, allowing NPs to accumulate. Active targeting involves engineering NPs to bind to specific cell surface receptor, like as integrins, that are often over-expressed in diseased cells.

Beyond drug delivery, NPs are showing promise in gene therapy for chronic lung conditions like COPD and monogenic diseases like cystic fibrosis & alpha-1 antitrypsin deficiency. While challenges remain with current gene therapy approaches (e.g., immune responses and transient expression), NP vectors can significantly enhance gene expression in the lungs. Cationic liposomes, sometimes combined with cell-penetrating peptides, have shown improved The absorption by cells in the respiratory tract, offering a promising avenue for future treatments.(42,43,44,45,46,)

4. APPLICATION OF NANOTECHNOLOGY IN SARS CoV 2 –

Nanoparticles (NPs) are significantly improving COVID-19 treatment by enhancing drug delivery and reducing side effects for medications like interferon-α and favipiravir. Biopolymeric NPs, for instance, lower toxicity and boost drug solubility. Beyond therapeutics, prevention remains key. This includes practices like mask-wearing, hand hygiene, and avoiding close contact with infected individuals. Healthcare workers require N-95 masks.

For diagnosis, PCR-based genetic tests detect early viral genomes, while serology tests (ELISA, luminescence, antibody tests) identify antibodies (IgG, IgM) later in the infection. Many of these diagnostic tools rely on nanomaterials.

Nanotechnology is also driving the rapid expansion of COVID-19 vaccine and novel therapies, through many nanomedicine-based drugs and NP-delivered vaccines in development or clinical trials. This innovative approach is crucial in the ongoing fight against the pandemic.(47,48,49,50,51,)

5. APPLICATION OF NANOTECHNOLOGY FOR TACKLING UROLOGICAL DISEASE –

In recent decades, nanoparticle (NP) research has surged in clinical studies, proving to be a highly reputable scientific discipline globally. Its application in managing multidrug-resistant pathogens and other illnesses, including urinary tract infections (UTIs), shows immense promise. Research has indicated that silver and zinc nanoparticles against uropathogens.

NPs, composed of various material such as metals, lipids, and polymer, can enhance the in vivo performance of drugs and circumvent the urinary tract's physiological obstacles. By modifying NP surfaces with mucus-penetrating moieties or hydrophobic ligands, drugs can traverse epithelial interfaces more efficiently.

Advantages of Nanoparticles in Treatment- Nanomaterials offer several key benefits:

- **Reduced Side Effects:** Through active or passive targeting, NPs can minimize drug exposure to healthy tissues.
- **Enhanced Efficacy:** Nanoparticle-based antimicrobials boast greater therapeutic efficacy, prolonged stability, and sustained drug release compared to traditional methods.
- **Targeting Intracellular Pathogens:** Unlike conventional antibiotics that struggle with dormant intracellular pathogens causing recurrent infections, nano-antibiotics can effectively target these reservoirs, reducing disease recurrence. These NPs either possess inherent antimicrobial qualities or boost antibiotic effectiveness.

Nanotechnology has significantly advanced the analysis & dealing with various cancers, including urothelial carcinoma**,** which is the tenth most prevalent cancer globally. Metallic, lipid, and polymeric NPs are being used to improve bladder cancer therapy. NPs can increases the solubility of poorly soluble drugs and function as drug delivery systems (DDS) to enhance drug effects and interactions within tumors.

The multifunctional nature of nanomaterials makes them highly valuable in cancer therapy. They can deliver controlled thermal doses for hyperthermia, combine multiple therapeutic agents for simultaneous delivery to cancerous areas, and be modified with compounds to promote receptor binding. Furthermore, combining drugs with nanomaterials can allow for faster accumulation in tumors and quicker clearance from the bloodstream, leading to comparable therapeutic activation with significantly lower overall exposure.

The field of nanotechnology is set to revolutionize patient care for bladder cancer, offering exciting improvements where traditional treatments have long remained stagnant.(52,53,54,55,56,57,58,)

6. NANOTECHNOLOGY IN VACCINE DELIVERY –

Nanomaterials are transforming vaccine development by creating nanocarriers **t**hat deliver vaccines more effectively. Both pathogenic and non-pathogenic nanocarriers can trigger robust immune response, as well as cell-mediated immunity, which is crucial for fighting intracellular infections.

Designing nanocarriers that improve lymphatic drainage **or** dendritic cell (DC) uptake can significantly enhance vaccine efficacy, particularly for CD8++ T cell responses. This targeted delivery to DCs in lymphoid organs can also reduce the required vaccine dose, improving safety.

Benefits of Nanotechnology in Tumor Vaccines

Nanotechnology offers several advantages for tumor vaccines compared to traditional methods:

- **Protection:** Shields vaccines from rapid degradation.
- **Targeting:** Uses ligands and antibodies to specifically target DCs.
- **Delivery:** Facilitates the delivery of vaccines, antigens, adjuvants, and other anticancer agents.
- **Enhanced Immune Response:** Improves cross-presentation to trigger stronger immune responses.
- **Improved Antigen Presentation:** Delivers antigens to targeted sites, boosting their bioavailability and dispersion.
- **Prolonged Retention:** Increases the time tumor antigens remain in the body.

While vaccination is a vital tool against viral infections, traditional vaccines often face limitations like poor immune activation, toxicity, unstable in vivo performance, and strict storage requirements. Nano-vaccines effectively address these drawbacks by inducing and enhancing both humoral and cellular immune reactions more efficiently.

Currently, nanomedicine is also playing a key role in developing preventative and therapeutic strategies for coronavirus infections, where there's no specific antiviral treatment. AI and computational techniques are accelerating drug discovery for new viruses, and drug repurposing based on genomic and proteomic analyses is being explored for rapid recovery.(59,60,61,62,63,)

7. NANOTECHNOLOGY USED FOR KIDNEY DISEASE –

The kidney is an ideal target for nanomaterial-based therapies due to its role in excretion, susceptibility to drug toxicity (especially in transplants), and interaction with blood. Its natural filtration system, which rapidly eliminates particles under 10 nm, can be exploited for kidney disease monitoring, diagnosis, and treatment.

Nanoparticle (NP) delivery systems can significantly improve kidney disease treatment by lowering overall drug dosages and reducing side effects. While local drug delivery with NPs shows promise, more research is needed for clinical translation. NPs can also help distinguish between healthy and diseased kidney functions, aiding research.

For chronic kidney disease (CKD), current treatments like ACE inhibitors and immunosuppressants can't fully restore kidney function. NPs offer a breakthrough for targeted drug delivery in CKD and acute kidney injury (AKI) by managing particle size, charge, and surface properties. This allows for precise delivery of renal protective medications, enhancing therapeutic effects and minimizing toxicity, particularly by focusing on reactive oxygen species, which are crucial in AKI.(64,65,66,67,68,)

8. NANOTECHNOLOGY USED IN PATCHES –

Transdermal Drug Delivery (TDD) uses nanocarriers to deliver remedies through the skin, leveraging structures like hair follicles or damaged skin for better penetration and retention. Nanoparticles (NPs) are promising for TDD Because of its huge area of surface and compact stature, enhancing drug absorption.

However, challenges exist: NPs can accumulate in hair follicles, limiting continuous delivery to deeper skin layers. Other drawbacks include potential skin irritation, limited drug loading capacity, toxicity concerns (e.g., chloramine-T is banned in some regions), storage issues, and high production costs. While suitable for low-dose drugs, increasing the dose requires larger application areas, leading to patient dissatisfaction and higher expenses.

Despite these, nanomedicines are widely used in cosmetics for anti-aging and aesthetic purposes, raising concerns about potential health risks like cancer if they cross biological barriers. Therefore, public awareness of nanomedicine impacts is crucial.

When treating skin malignancies such as basal cell carcinoma, squamous cell carcinoma, and melanoma, NPs offer a less invasive, more targeted approach with enhanced drug penetration compared to traditional surgical excision. NP-based formulations, even when combined with techniques like iontophoresis, have shown superior therapeutic outcomes in suppressing tumor growth and promoting cell death.(69,70,71,72,73,)

9. APPLICATION OF NANOTECHNOLOGY IN HYPERTENSION –

Many hypertension medications have poor water solubility and short half-lives. Nanotechnology, especially nanoemulsions, offers a promising solution for improved drug delivery. Oral nanoemulsions are preferred due to their convenience, precise dosing, and patient compliance.

Once ingested, nanoemulsions interact with the gastrointestinal tract, where gastric lipase breaks down their lipid layer, and bile components form micelles that enhance drug solubility and absorption via endocytosis or transcytosis.

Beyond hypertension, nanomedicines are being explored for cardiac healing**.** For instance, fibrinogen, abundant in injured heart tissue but not healthy myocardium, can be a target. PEGylated liposomes linked to antimyosin antibodies are suggested for delivering drugs and imaging agents to infarcted hearts. Similarly, iron oxide nanocrystals conjugated with Annexin V can detect early apoptotic cells after ischemia-reperfusion injury. Identifying surface-level cardiac targets is crucial for effective drug accumulation at the infarction site.

The capacity of nanomedicines to lessen blood pressure swings is a major advantage for those with hypertension, improve drug concentration, & lower dosages. Transdermal nanoformulations, like ilaridipine invasomes, have shown significant blood pressure reduction, highlighting the potential of nanomedicines to enhance hypertension treatment and patient compliance, offering a new perspective on chronic disease management.(74,75,76,77,)

10. APPLICATION OF NANOTECHNOLOGY IN OCULAR DISEASES –

The intricate anatomy and inherent obstacles of the eye make it difficult to treat eye problems effectively. Conventional techniques, such as ocular drops, frequently have brief residence periods and poor drug penetration.

Nanotechnology offers a promising solution. Nanomedicine-driven drug delivery systems may overcome ocular barrier, including the blood-retinal barrier, to improve drug bioavailability and therapeutic efficacy. These systems can also sustain drug release, reducing dosing frequency and side effects.

Among the main benefits of using nanoparticles (NPs) for ocular administration are:

- **Enhanced Corneal Penetration:** NPs can more effectively cross the cornea.
- **Increased Ocular Residence Time:** They stay in the eye longer, improving drug exposure.
- **Improved Bioavailability:** More medication reaches the target tissues.

Factors Such as shape, particle size, surface charge, & functional groups, all influence the safety and efficacy of nanomedicines in the eye. While research suggests NPs are a viable ophthalmic delivery mechanism, further clinical trials are needed to bring them into widespread use.(78,79,80,81,82,)

11. APPLICATION OF NANOTECHNOLOGY IN ALZHEIMER DISEASE –

For years, researchers have explored nanomaterials in precision medicine, particularly for neurological conditions like Alzheimer Disease**,** where the blood-brain barrier limits drug access. Nanotechnology provides a solution for this FDA-approved nanocarriers, ranging widely in size, are used to deliver commercial drugs for AD and brain tumors. These nanomedicines come in various forms, mainly lipid-based, organic, or metallic nanoparticles (NPs).

Nanotechnology also enhances biosensors for AD. Biosensors combine biological recognition elements (like antibodies) with energy converters to detect analytes for qualitative and quantitative analysis. Nanotechnology has enabled new signal transduction methods, leading to advanced immunosensors. For example, silver nanoparticles (SNPs) from certain plant extracts have shown improved anti-AChE and antioxidant activity in vivo, suggesting they could boost AChE levels and reduce oxidative stress in AD.

Silica particles are also versatile in nanotechnology, with tunable porosity making them excellent drug delivery vehicles or therapeutic reservoirs. Promising experimental results with silica-based NPs have been seen in managing neurological conditions like AD and Friedreich's ataxia.

The multi-causal nature of AD is being addressed through advances in biology, chemistry, and radiography, which provide accessible biomarkers, paving the way for targeted nanomedicine treatments.(83,84,85,86,87,)

12. APPLICATION OF NANOTECHNOLOGY IN OLIGO-NUCLEOTIDE DRUG DELIVERY –

Oligonucleotide medicines (ONs), short DNA or RNA sequences, offer significant therapeutic potential by interacting with disease-related genes and regulating gene transcription. However, a major hurdle for their widespread use is efficient delivery, especially to tissues outside the liver.

ONs must overcome multiple physiological barriers to reach their intracellular targets. While local administration via intravitreal (for eyes) and intrathecal (for brain/spinal cord) routes has shown effectiveness, systemic delivery remains challenging.

Current strategies to address this involve:

- **Chemical modifications:** Altering the ONs' composition.
- **Bioconjugations:** Linking ONs to other molecules.
- **Nanocarriers:** Utilizing tiny delivery vehicles.

These nanocarriers, often complex self-assemblies, are crucial for effective ON delivery, but balancing their sophistication with scalable manufacturing is key for practical implementation. The goal is to develop highly effective, low-toxicity delivery mechanisms to enhance the "druggability" of these promising therapeutics, with nucleolipids showing potential as low-toxicity endogenous macromolecule carriers. (88,89,90,91,)

13. SIGNIFICANCE OF NANOTECHNOLOGY IN PARKINSON DISEASE –

Nanoparticles (NPs) are significantly enhancing Parkinson's Disease (PD) treatment by improving drug efficacy and enabling the targeted drug delivery across the blood-brain barrier. This approach reduces side effects and boosts patient compliance, offering PD sufferers a better quality of life.

The NDDS represents the auspicious future for neurological disorders. Carriers like liposomes, nanoemulsions, and niosomes greatly improve the efficiency of anti-Parkinsonian drugs like Levodopa & curcumin.

The goal is to develop non-invasive, biodegradable nanocarriers that can cross the BBB, provide sustained drug release, and achieve high drug uptake with precise targeting. NPs are being explored to prolong drug release, bypass defense mechanisms, and access the central nervous system.

Optimizing NP surfaces can enable non-invasive delivery methods like intranasal administration. However, further research into PD's neuropathology, delivery mechanisms, surface enhancements, and the biocompatibility/selectivity of catalytic nanoparticles is crucial for these advancements to become widely available. (92,93,94,95,)

CONCLUSION –

Recent developments in nanotechnology have transformed medicine by enabling precision targeting, controlled release, and increased therapeutic efficacy in drug delivery systems. Drugs may now be delivered to precise locations with the help of nanocarriers, which lowers adverse effects and enhances patient outcomes. The blood-brain barrier and other biological barriers may be crossed by nanocarriers, which creates new therapeutic avenues for disorders that were previously untreatable. Furthermore, customized medication compositions that meet the specific requirements of each patient are made possible by the adjustable qualities of nanomaterials. Furthermore, because nanocarriers are multifunctional, they may carry many therapeutic compounds at the same time, allowing for combination treatments and synergistic effects. This multidimensional pathogenic mechanism-based approach has potential for treating complicated disorders. The benefits include increased bioavailability, increased circulation time, and the potential for tailored therapy, indicating a promising future in pharmaceuticals with far-reaching consequences for healthcare.

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