IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Recent developments and future prospects in Nanoparticles-based Drug Delivery and Targeting Systems for Precision Medicine- A Review

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Abstract: Nanoscience and nanotechnology are highly relevant today, with nanoparticles being widely utilized across various fields. They play a crucial role in drug delivery systems, offering precise targeting and controlled release. Additionally, nanoparticles are integral to diagnostic applications and imaging techniques, enhancing the accuracy and efficiency of medical diagnostics and treatment monitoring. Integrating drugs into nanocarriers is an effective strategy for achieving targeted and sustained drug delivery. In this review, we will explore recent advancements in widely used nanoparticles, covering their properties, design, and applications in drug delivery systems. Various types of nanocarriers, including solid nanoparticles, liposomes, dendrimers, polymeric nanoparticles, polymeric micelles, virus-like nanoparticles, carbon nanotubes, and mesoporous silica nanoparticles, are employed in this approach. Each type offers unique advantages for enhancing drug delivery precision, prolonging drug release, and improving therapeutic outcomes. We will examine how these nanoparticles address challenges in precision medicine by overcoming diverse barriers, ultimately enhancing patient outcomes through improved therapeutic efficacy and personalized treatment approaches.

Keywords: Nanoparticles, precision medicine, target drug delivery, therapeutic efficacy, evaluation, smart drug delivery, clinical application.

1. INTRODUCTION

The prefix "nano" has found in last decade an ever increasing application or use to different fields of the knowledge and purpose. Nanoscience, nanotechnology, nanochemistry are the new nano-containing terms that occur regularly in scientific reports, in popular books, magazines and newspapers. According to the **NNI (*National Nanotechnology Initiative*)**, nanoparticles are structures of sizes ranging from **1 to 100 nm** in at least one dimension.

Nanoscience and nanotechnology provides opportunities for the development of medical applications, where conventional techniques may reach their limitation. In pharmaceutical nanoparticles are defined as solid, submicron-sized (<100 nm in diameter) drug molecules that may or may not be biodegradable. Nanoparticle is a combined name for both **nanosphares** and **nanocapsules**. One of the most exciting aspects of nanotechnology is its potential in medicine, particularly in drug delivery, diagnostics, and tissue engineering. Nanoparticles can be engineered to target specific cells, such as cancer cells, allowing for precise treatment with minimal side effects. In diagnostics, nanoscale sensors can detect diseases at very early stages, significantly improving treatment outcomes. Nanospheres are spherical nanoparticles with diameters ranging from 1 to 100 nanometers. Due to their uniform size and shape, they are utilized in various applications across fields such as medicine, electronics, and materials science. In pharmaceuticals, nanospheres can act as drug carriers, enhancing the delivery and release of therapeutic agents while minimizing side effects. Their large surface area allows for the efficient encapsulation of drugs and targeted delivery to specific cells or tissues. In diagnostics, nanospheres are used as contrast agents in imaging techniques due to their ability to improve signal detection. Their versatility and tunable properties make them valuable in developing advanced materials and coatings with enhanced mechanical, optical, or catalytic properties. Despite their benefits, ongoing research is essential to understand their long-term impact on health and the environment. Nanocarriers are nanoparticles designed to transport and deliver therapeutic agents precisely to targeted cells or tissues. In pharmacy, they play a crucial role in enhancing

drug delivery and efficacy while minimizing side effects. Common types of nanocarriers include liposomes, which are lipid-based vesicles that encapsulate drugs, and polymeric nanoparticles, which offer controlled release and improved stability. This targeted approach improves the bioavailability of drugs and reduces systemic toxicity. Additionally, surface modifications of nanocarriers can enhance their ability to navigate biological barriers and interact with specific cellular receptors. Liposomes are spherical vesicles composed of lipid bilayers that encapsulate drugs, improving their bioavailability and targeting. Polymeric nanoparticles, such as those made from poly lactic-co-glycolic acid (PLGA), offer controlled release and stability. Dendrimers are highly branched polymers with functional groups that enable precise drug attachment and release. Nanomicelles, formed from amphiphilic surfactants, encapsulate hydrophobic drugs and improve solubility. Quantum dots are semiconductor nanoparticles used for imaging and diagnostics due to their bright fluorescence.

They are driving revolutionary advancements with the potential to enhance drug delivery, improve therapeutic efficacy, and minimize side effects. Nanotechnology enables the design of nanoparticles that can encapsulate drugs, allowing for targeted delivery to specific cells or tissues, such as cancer cells, while sparing healthy tissues. One of the key innovations in pharmaceutical nanotechnology is the development of nanocarriers, such as liposomes, dendrimers, and polymeric nanoparticles, which can encapsulate both hydrophilic and hydrophobic drugs. These nanocarriers can be engineered to release their payload in response to specific physiological conditions or external stimuli, such as changes in pH or temperature, enhancing the precision and control of drug release. Additionally, surface modification of these nanoparticles can improve their stability in the bloodstream and extend their circulation time, leading to prolonged therapeutic effects.

Nanotechnology also plays a crucial role in the development of diagnostic tools and imaging agents. Quantum dots, for example, are semiconductor nanoparticles that can be used as fluorescent markers in imaging techniques, allowing for the visualization of biological processes at the molecular level. This can lead to earlier detection of diseases and more accurate monitoring of treatment progress. It has the potential to advance personalized medicine by enabling the design of drug delivery systems tailored to individual genetic profiles. This can enhance the efficacy of treatments and minimize the risk of adverse drug reactions by ensuring that medications are delivered in optimal doses and at the right time. In addition to drug delivery and diagnostics, nanotechnology is also contributing to the development of novel pharmaceutical formulations. Nanoparticles can improve the solubility and bioavailability of poorly soluble drugs, making it possible to administer these drugs more effectively and reduce the need for higher doses.

Overall, nanoscience and nanotechnology are poised to significantly impact the field of pharmacy by offering innovative solutions for drug delivery, diagnostics, and personalized medicine. These advancements hold promise for more effective treatments, improved patient outcomes, and a deeper understanding of complex biological processes.

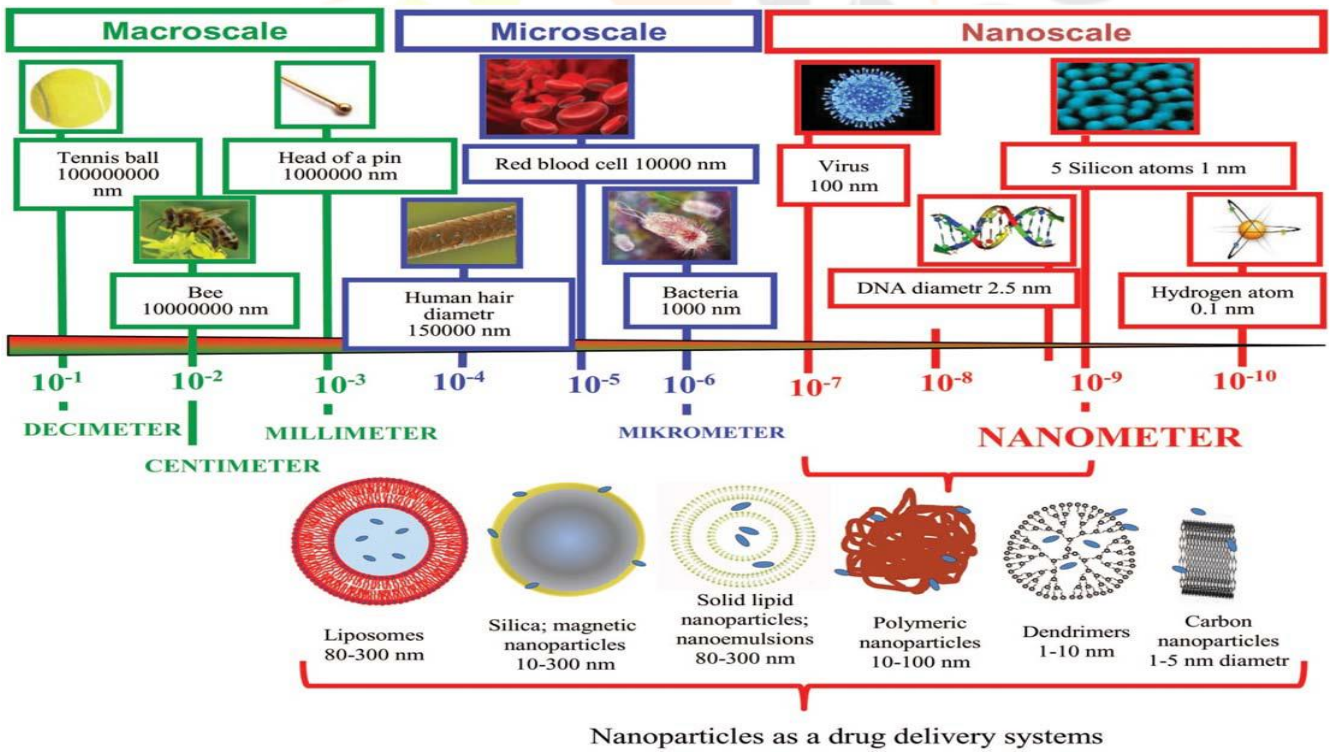


Fig-1: Nanoparticles drug delivery systems

2. PRECISION MEDICINE:

Precision medicine is an innovative approach to healthcare that tailors treatment and prevention strategies to an individual's unique genetic, environmental, and lifestyle factors. Unlike traditional medicine, which often applies a one-size-fits-all method, precision medicine leverages advancements in genomics, big data, and bioinformatics to understand the molecular basis of diseases.

By identifying specific genetic mutations or biomarkers, it allows for more accurate diagnoses and the development of targeted therapies. This personalized approach enhances treatment effectiveness, minimizes side effects, and can even predict disease risk, enabling early interventions. It is transforming healthcare by shifting the focus from treating diseases to preventing them and promoting overall health, offering the potential for more effective and efficient medical care tailored to each patient's unique profile. Its approach promises to transform healthcare by making treatments more personalized, predictive, and preventative, ultimately improving patient outcomes and advancing medical science.

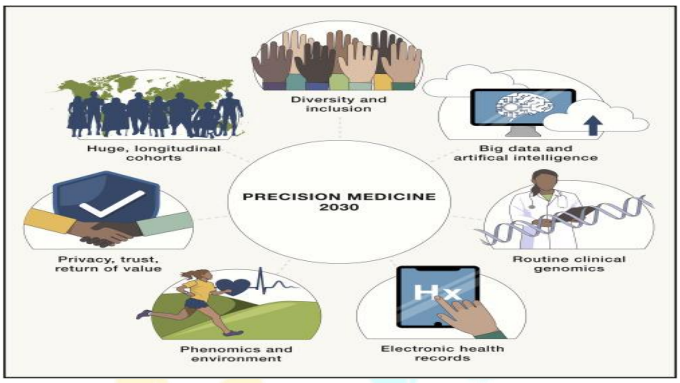


Fig 2: Seven opportunities for precision medicine by 2030

Table 1

Envisioning how precision medicine will affect clinical medicine and research in the next decade

S. No	Clinical applications	Where we are today	Where we will be in 2030
1.	Genomics for disease	Primarily limited to rare disease and select cancers.	Genomics is routine. Genetic causes and targeted therapies are discovered for many "common" diseases. Microbiome measures are routinely included.
2.	Pharmacogenomics (PGx)	Common in cancer and within select applications of older medications at select sites.	Genome-aware EHRs make PGx easy and automatically update rules from central guidelines. New PGx associations discovered from clinical data.
3.	Genomics for healthy individuals	In research, whole-genome sequencing and search for mutations in one of the ACMG59 genes, present in about 3% of people. Variant interpretation is hard.	ACMG59 grows to > 200, variant interpretation improved by huge, diverse sequenced populations. Cell-free DNA becomes a mainstay of cancer screening
4.	Environmental influences on health	Patient-reported habits and exposures	Geocode-based exposure linkage Real time monitoring of multiple environmental exposures Precision nutrition
RESEARCH APPLICATIONS			
1.	Population demographics	>80% European ancestry	>50% non-European ancestry
2.	Routinely available data	Surveys of health conditions, lifestyle, behavior, and diet. GWAS data, lab assays, structured EHR data, and geocoded exposure linkages.	Whole genomes, lab assays, surveys, full EHRs, environmental, genomic and sensor data. Includes imaging, narrative, geocoded, and continuous monitoring approaches to clinical care, activity, precision nutrition, and environment.
3.	Size of cohorts used in analysis	Up to 500K, data downloaded and manually harmonized to sets of several million	>100M using cloud-based federated analyses facilitated by common standards
4.	Largest genomic studies performed on a trait	>1M (GWAS)	>50M (GWAS) >2M (WGS)
5.	Cost of a whole genome	$500	$20

3. EARLY PERIOD OF NANOPARTICLES

The early period of nanoparticle-based drug delivery systems marked a significant shift in the field of medicine and pharmacy, laying the groundwork for the advanced drug delivery technologies we see today. Initially, the concept of using nanoparticles as carriers for drugs emerged from the need to overcome the limitations of conventional drug delivery methods, such as poor solubility, rapid degradation, and non-specific distribution of drugs within the body.

During this early phase, researchers began exploring various materials to create nanoparticles, including lipids, polymers, and metals. Lipid-based nanoparticles, like liposomes, were among the first to be extensively studied and used due to their biocompatibility and ability to encapsulate both hydrophilic and hydrophobic drugs. Early liposomal formulations, such as those developed in the 1970s and 1980s, demonstrated the potential of nanoparticles to improve the pharmacokinetics and bio distribution of drugs, leading to enhanced therapeutic efficacy and reduced toxicity.

Another key development in this period was the introduction of polymeric nanoparticles, which offered greater control over drug release profiles. These nanoparticles could be engineered to degrade gradually in the body, providing sustained release of the drug over time. Researchers also began to explore surface modification techniques to enhance the targeting capabilities of nanoparticles. For example, by attaching specific ligands or antibodies to the surface of nanoparticles, scientists could direct them to specific cells or tissues, increasing the precision of drug delivery.

The early successes in nanoparticle-based drug delivery systems sparked significant interest and further research, leading to the development of more sophisticated delivery platforms. These early efforts laid the foundation for the targeted, controlled, and personalized drug delivery systems that are now integral to modern medicine, particularly in the treatment of complex diseases like cancer, where precision and efficacy are paramount.

4. Recent nanoparticles based drug delivery systems and applications:

Recent advancements in nanoparticle-based drug delivery systems have revolutionized the field of medicine, offering highly sophisticated methods for delivering therapeutic agents with unprecedented precision and efficacy. These modern systems have expanded upon early designs, incorporating advanced materials like dendrimers, quantum dots, and gold nanoparticles, each tailored to improve drug loading capacity, stability, and targeted delivery. Nanoparticle-based drug delivery systems have seen significant advancements in recent years, offering promising solutions for targeted therapy, reduced side effects, and improved efficacy in the medical field. One of the most significant innovations is the development of multifunctional nanoparticles that can perform multiple roles, such as targeting, imaging, and therapy, all in one platform. For example, some nanoparticles are now designed to deliver drugs directly to cancer cells while simultaneously acting as imaging agents, allowing for real-time tracking of the treatment process through techniques like MRI or fluorescence imaging. Here are some key developments:

4.1 Targeted Drug Delivery

- **Active Targeting**: Nanoparticles can be engineered to specifically target diseased cells, such as cancer cells, by attaching ligands (like antibodies or peptides) that bind to receptors over expressed on these cells.
- **Passive Targeting**: Enhanced permeability and retention (EPR) effect allow nanoparticles to accumulate more in tumour tissues due to their leaky vasculature, which is often seen in tumours.

4.2 Stimuli-Responsive Nanoparticles

- **pH-Responsive Systems**: These nanoparticles release their drug payload in response to the acidic environment found in certain disease sites, such as tumours or inflamed tissues.
- **Temperature-Sensitive Nanoparticles**: Some nanoparticles are designed to release drugs at specific temperatures, which can be applied externally to trigger release at the target site.
- **Magnetic and Light-Activated Systems**: Magnetic nanoparticles can be directed to a specific site using an external magnetic field, while light-sensitive nanoparticles release drugs upon exposure to certain wavelengths of light.

4.3 Polymeric Nanoparticles

- **Biodegradable Polymers**: These nanoparticles, made from materials like PLGA (polylactic-co-glycolic acid), are used to encapsulate drugs, providing controlled release over time as the polymer degrades naturally in the body.
- **Nanogels**: These hydrogel nanoparticles can swell and shrink in response to environmental changes, offering another method for controlled drug release.

4.4 Lipid-Based Nanoparticles

- **Liposomes**: These are spherical vesicles with a lipid bilayer that can encapsulate both hydrophilic and hydrophobic drugs, improving the solubility and stability of drugs and allowing for targeted delivery.
- **Solid Lipid Nanoparticles (SLNs)** and **Nanostructured Lipid Carriers (NLCs)**: These systems improve drug stability and controlled release, often used for poorly water-soluble drugs.

4.5 Dendrimers

- **Highly Branched Polymers**: Dendrimers have a well-defined, tree-like structure that allows for precise drug loading and multivalent interactions, making them suitable for targeted drug delivery.

4.6 Nanoparticles in Immunotherapy

- **Cancer Vaccines**: Nanoparticles are being used to deliver antigens and adjuvants directly to immune cells, enhancing the body's immune response against tumours.
- **Checkpoint Inhibitors**: Nanoparticles are also being employed to deliver checkpoint inhibitors, which can block proteins that prevent immune cells from attacking cancer cells.

4.7 Clinical Translation and Challenges

- **FDA-Approved Nanomedicines**: Some nanoparticle-based drugs have already been approved for clinical use, such as Doxil (a liposomal formulation of doxorubicin) for cancer treatment.
- **Challenges**: Despite the progress, challenges remain in the large-scale production, stability, and potential toxicity of nanoparticles, as well as regulatory hurdles for new nanomedicines.

4.8 AI Change the future of Precision medicine

- **Enhanced Disease Prediction and Prevention**: AI can analyze vast amounts of genetic and environmental data to predict disease risks with greater accuracy. This allows for earlier interventions, personalized prevention strategies, and more precise monitoring, potentially reducing the incidence and severity of diseases.
- **Improved Drug Development and Targeted Therapies**: AI accelerates the drug discovery process by identifying potential therapeutic targets and predicting how patients will respond to different treatments.
- **Personalized Treatment Plans**: AI can integrate and analyze diverse data sources, including genomics, medical history, and lifestyle factors, to create highly individualized treatment plans. This ensures that patients receive the most appropriate therapies, improving outcomes and optimizing healthcare resources.
  Page no.:

5. ADVANTAGES

Nanoscience and nanotechnology have introduced numerous advantages in the medical field, revolutionizing diagnosis, treatment, and prevention strategies. Here some benefits are:

1. Targeted Drug Delivery: Nanoparticles can be engineered to deliver drugs specifically to diseased cells, reducing damage to healthy tissues and minimizing side effects.

2. Improved Drug Solubility: Nanotechnology can enhance the solubility and bioavailability of poorly soluble drugs, allowing for more effective treatments.

3. Controlled Drug Release: Nanoparticles can be designed for sustained or controlled drug release, ensuring a steady therapeutic effect and reducing the frequency of dosing.

4. Reduced Drug Resistance: By delivering drugs directly to the target site, nanotechnology can help overcome drug resistance, particularly in cancer therapy.

5. Enhanced Imaging Techniques: Nanoparticles can be used as contrast agents in imaging technologies like MRI, PET, and CT scans, providing clearer and more precise images for diagnosis.

6. Early Disease Detection: Nanosensors can detect biomarkers at very low concentrations, enabling early diagnosis of diseases such as cancer, before symptoms appear.

7. Personalized Medicine: Nanotechnology allows for the development of personalized treatments based on a patient's genetic makeup, improving efficacy and reducing adverse reactions.

8. Minimally Invasive Procedures: Nanotechnology enables minimally invasive procedures, such as nanorobots performing microsurgeries, reducing recovery time and surgical risks.

9. Regenerative Medicine: Nanomaterials are used in tissue engineering and regenerative medicine to promote the growth and repair of tissues, improving outcomes for injuries and degenerative diseases.

10. Enhanced Vaccine Delivery: Nanoparticles can be used to develop more effective vaccines by enhancing the delivery and presentation of antigens to the immune system.

11. Biosensors for Real-Time Monitoring: Nanoscale biosensors can monitor biological processes in real-time, providing immediate feedback for better disease management.

12. Improved Biocompatibility: Nanomaterials can be engineered to be more biocompatible, reducing the risk of immune rejection in implants and other medical devices.

6. DISADVANTAGES

While nanoscience and nanotechnology offer significant benefits in the medical field, they also come with several disadvantages and challenges. Here are 7 key points:

1. **Toxicity Concerns**: Some nanoparticles can be toxic to cells and tissues, potentially leading to unintended side effects, including inflammation, oxidative stress, and organ damage.
2. **Environmental Impact**: The production and disposal of nanomaterials may have adverse effects on the environment, including pollution and accumulation in ecosystems.
3. **Unknown Long-Term Effects**: The long-term health effects of exposure to nanoparticles are not yet fully understood, raising concerns about their safety in medical applications.
4. **Difficulty in Regulation**: The small size and unique properties of nanoparticles make it challenging to regulate their use in medicine, potentially leading to inconsistent safety standards.
5. **High Cost**: The development and production of nanotechnology-based medical treatments can be expensive, potentially limiting accessibility and increasing healthcare costs.

7. MECHANISM OF TARGETED DRUG RELEASE:

Targeted drug release is a sophisticated mechanism in pharmacy designed to deliver medication directly to a specific site within the body, thereby maximizing therapeutic effects while minimizing side effects. This approach often involves the use of carriers like nanoparticles, liposomes, or biodegradable polymers that encapsulate the drug. These carriers are engineered to recognize and bind to specific cells or tissues, often through surface markers unique to the target. Once the carrier reaches its destination, it can release the drug in response to certain stimuli, such as pH changes, temperature, or specific enzymes present in the target area.

It is a significant advancement in pharmaceutical technology, focusing on delivering therapeutic agents specifically to diseased tissues or cells while sparing healthy ones. The process begins with the design of drug carriers, such as nanoparticles, liposomes, dendrimers, or micelles, which can encapsulate the drug. These carriers are often modified with ligands, antibodies, or peptides that can recognize and bind to specific receptors on the target cells. For example, cancer cells often over express certain receptors or proteins on their surface, which can be exploited to guide the drug-laden carrier directly to the tumour. Targeted drug release is a three step process: (i) through multivalent receptor–ligand interactions nanocarrier binds with the receptors of the target cell, (ii) through endocytosis drug nanocarrier enters into the cell and (iii) in the last step drug release takes place.

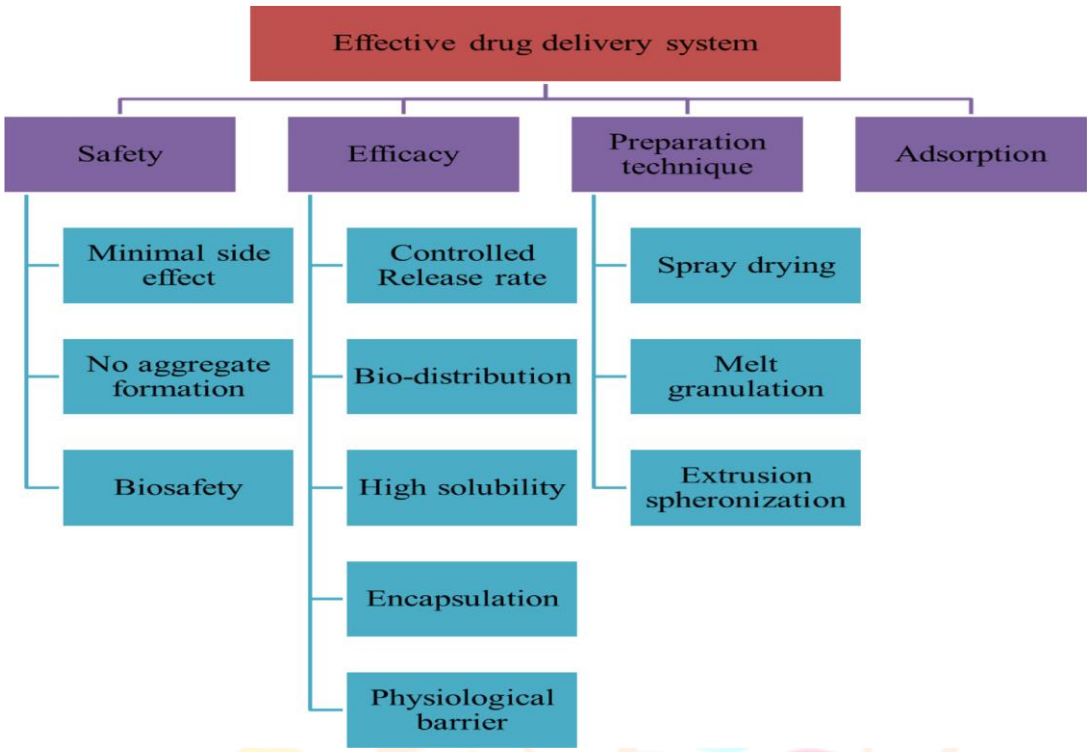


Fig 3: Factors involved in designing of effective drug delivery system.

Upon reaching the target site, the drug is released from its carrier in a controlled manner. For instance, tumour environments are typically more acidic than normal tissues, allowing pH-sensitive carriers to release their payload specifically within the tumour site. Alternatively, external stimuli such as heat, light, or magnetic fields can be applied to trigger drug release at the desired location.

The development of smart drug delivery systems has introduced the possibility of multi-step targeting, where the drug carrier first targets a general area, such as the bloodstream near a tumour, and then further localizes to the specific cancer cells within that area. Overall, targeted drug release is a dynamic and rapidly evolving field in pharmacy, with ongoing research aimed at improving targeting accuracy, carrier biocompatibility, and the range of stimuli that can trigger drug release. These advancements hold the promise of more effective and personalized therapies for a wide range of diseases. Targeted drug delivery can take place in cytosol and cell membrane by interacting with lipid membrane. Drug release can be achieved through two approaches: by cleaving linkers or by controlling the carrier.

a) **By cleaving linkers:** The mechanism of drug release through cleaving linkers in nanoparticles involves breaking the chemical bonds that connect the drug to the nanoparticle carrier. This cleavage can be triggered by specific environmental conditions, such as changes in pH, temperature, or the presence of certain enzymes. Once the linkers are cleaved, the drug is released from the nanoparticle, allowing it to exert its therapeutic effect at the target site.
b) **By controlling the carrier:** The mechanism of drug release by controlling the carrier in nanoparticles involves manipulating the physical or chemical properties of the nanoparticle itself. This can include adjusting the nanoparticle's degradation rate, altering its permeability, or applying external stimuli like heat, light, or magnetic fields. These controlled changes allow for precise timing and location of drug release, ensuring that the therapeutic agent is delivered effectively to the desired site within the body.

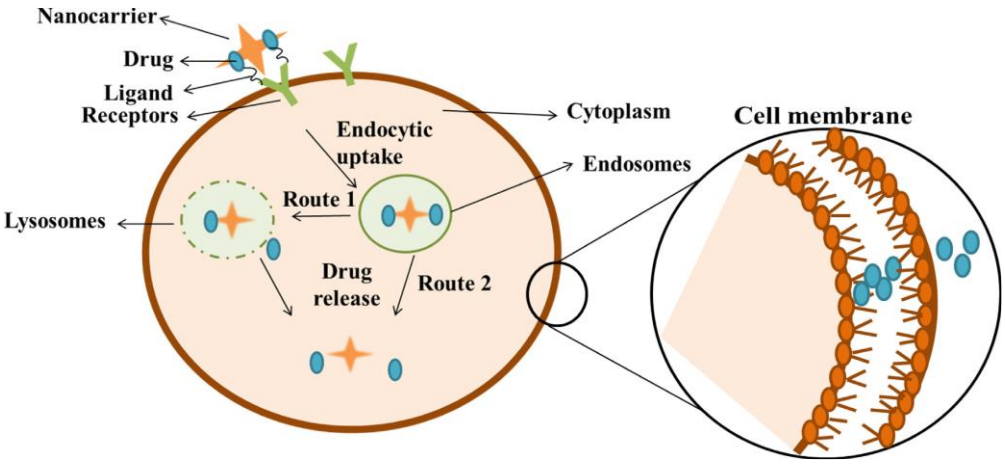


Fig 4: Schematic illustration of target drug release system in cytosol and cell membrane.

8. TYPES OF NANOPARTICLES:

The classes of nanoparticles listed below are all very general and multi-functional; however, some of their basic properties and current known uses in nano medicine are described here:

1) Metal Nanoparticles

2) Polymeric Nanoparticles

3) Lipid-Based Nanoparticles (LBN)

4) Dendrimers

5) Ceramic Nanoparticles

6) Quantum dots (QD)

7) Carbon-Based Nanoparticles

8) Magnetic Nanoparticles

9) Protein-Based Nanoparticles

10) Hybrid Nanoparticles

8.1 Metal Nanoparticles:

Metal nanoparticles, including gold, silver, and iron oxide nanoparticles, have garnered significant attention for their diverse applications and therapeutic potential. Gold nanoparticles (AuNPs) are extensively used due to their unique optical properties, which enable them to be employed in imaging techniques like computed tomography (CT) and surface-enhanced Raman spectroscopy (SERS). They are also utilized in targeted drug delivery, where their surface can be functionalized with specific ligands to direct drugs to cancer cells, and in photothermal therapy, where they convert light into heat to destroy tumor cells.

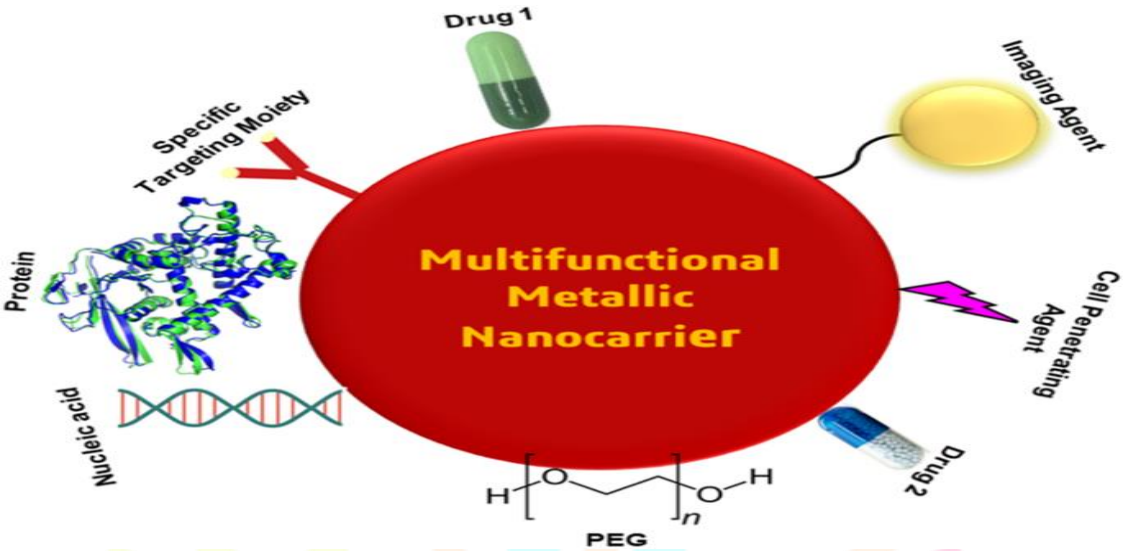


Fig 5: Metal Nanoparticles

Silver nanoparticles (AgNPs) are renowned for their potent antimicrobial properties, making them valuable in wound dressings, coatings for medical devices, and infection control. Their ability to release silver ions slowly helps in combating bacterial infections and promoting wound healing. Iron oxide nanoparticles, on the other hand, are primarily used in magnetic resonance imaging (MRI) as contrast agents due to their magnetic properties, which enhance imaging quality. Additionally, these nanoparticles are employed in magnetic hyperthermia, where they generate heat in response to an external magnetic field, aiding in the targeted treatment of cancerous tissues. Metal nanoparticles are mainly divided into three classes:

- **Gold Nanoparticles (AuNPs)**: Used in drug delivery, diagnostics and imaging.
- **Silver Nanoparticles (AgNPs)**: Known for antimicrobial properties, used in coatings and wound dressings.
- **Iron Oxide Nanoparticles**: Employed in magnetic resonance imaging (MRI) as contrast agents and in hyperthermia treatments for cancer.

8.2 Polymeric Nanoparticles:

Polymeric nanoparticles have become a pivotal tool in the medical field, particularly in drug delivery, gene therapy, and vaccine development. These nanoparticles are made from biocompatible and biodegradable polymers like PLGA (poly-lactic-co-glycolic acid)), chitosan, and PEG (polyethylene glycol), which offer several advantages, including controlled and sustained release of therapeutic agents. It can be engineered to encapsulate a wide range of drugs, protecting them from degradation and ensuring their stability until they reach the target site.

In drug delivery, these nanoparticles can be designed to release their payload over time, allowing for sustained therapeutic effects and reducing the need for frequent dosing. This is particularly beneficial in treating chronic conditions, where maintaining steady drug levels is crucial.

Table 2: List of drugs incorporated in polymeric nanoparticles for effective drug delivery.

S. No.	Drugs	Type of polymeric nanoparticle	Results
1.	Hydrophobic curcumin	Chitosan polymeric nanoparticle	Sustained release for 3 hours from the polymeric nanoparticle was observed. Highest inhibition zone for Pseudomo-nas aeruginosa was recorded as 3.2 cm
2.	Doxorubicin-triphenylphosphine	Polylactic-co-glycolic acid (PLGA) wrapped with bovine serum albumin	After 12 hours of treatment, MCF-7 cell, at pH 6.5 caused 74% of cell apoptosis. Tumor volume was reduced from 26 mm3 to 23 mm3.
3.	Curcumin	Poly(lactic-co-glycolic acid)-poly (ethylene glycol) (PLGA-PEG)	Drug loaded polymeric nanoparticle have 14 fold higher diffusivity in brain parenchyma compared to PLGA. Median area loss for drug loaded PLGA-PEG was recorded as 12.3%
4.	Ofloxacin	Polycaprolactone	Sustained release of drug for six hours was recorded

Polymeric nanoparticles are also being explored in gene therapy, where they can deliver DNA, RNA, or siRNA to specific cells, offering a promising approach to treat genetic disorders. Additionally, they play a role in vaccine development, where they can enhance immune responses by delivering antigens in a controlled manner, improving the efficacy and safety of vaccines. Overall, polymeric nanoparticles represent a versatile and highly effective platform in modern medicine.

- **Nanospheres**: Solid particles where the drug is dispersed throughout the polymer matrix. It a type of polymeric nanoparticle, are solid, spherical particles widely used in the medical field for drug delivery. They consist of a uniform polymer matrix where the drug is either dispersed throughout or adsorbed onto the surface. Nanospheres provide controlled and sustained release of drugs, enhancing therapeutic efficacy and reducing side effects.
- **Nanocapsules**: Have a core-shell structure where the drug is confined within the core and surrounded by a polymer shell. They are a specialized form of polymeric nanoparticles used in medicine, featuring a core-shell structure where the drug is enclosed within a cavity surrounded by a polymeric shell. This design allows for precise, controlled release of the therapeutic agent, protecting it from degradation until it reaches the target site.

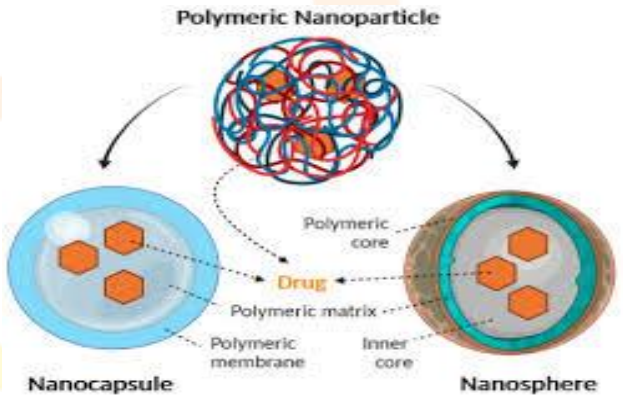


Fig 6: Nanospheres & Nanocapsules

8.3 Lipid-Based Nanoparticles (LBN):

Lipid-based nanoparticles, including liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), play a crucial role in the medical field, particularly in drug delivery and vaccine development. These nanoparticles are composed of biocompatible lipids, making them ideal for safely encapsulating both hydrophilic and hydrophobic drugs. Liposomes, for instance, consist of a lipid bilayer that can deliver drugs directly to target cells, reducing toxicity and enhancing therapeutic efficacy, especially in cancer treatment.

SLNs and NLCs are solid lipid-based systems that provide controlled and sustained drug release, improving the stability and bioavailability of drugs. They are also used in delivering genetic material, such as RNA, in vaccines, notably

demonstrated in mRNA vaccines for COVID-19. The ability of lipid-based nanoparticles to protect sensitive drugs and deliver them precisely where needed makes them a versatile and powerful tool in modern medicine.

8.3.1 Liposomes:

They are spherical lipid-based nanoparticles widely used in the medical field for drug delivery. Composed of one or more phospholipid bilayers surrounding an aqueous core, they can encapsulate both hydrophilic and hydrophobic drugs, protecting them from degradation and enhancing their stability. Liposomes are particularly effective in targeting drugs to specific tissues or cells, reducing side effects and improving therapeutic outcomes, especially in cancer therapy and antifungal treatments. Their biocompatibility and ability to deliver a wide range of therapeutic agents have made liposomes a cornerstone in advanced drug delivery systems and vaccine formulations.

Table 3: List of drugs incorporated in liposomes for effective drug delivery.

S. No.	Drugs	Liposome type	Results
1.	Paclitaxel	Chitosan oligosaccharide conjugated Pluronic P123 polymers	Inhibited 86.4% of tumor
2.	Bupivacaine	Unilamellar	Sustained drug release was recorded for 6 days
3.	Paclitaxel	Glutamic oligopeptides-RGD peptide (PTXGlu6-RGD-Lip)	HAP binding % showed that Paclitaxel (from PTX-Glu6-RGDLip) in metastatic bones was 5–8 times higher than free drug. Suggesting improved targeting efficacy
4.	Doxorubicin	Thioether phosphatidylcholines liposomes	The minimum average tumor weight was recorded as 0.78 g by samples treated with Doxorubicin loaded liposome. In the presence of 10 mM H_2O_2, 80% of the drug was released observed suggesting the improved reactive oxygen species (ROS) triggered release

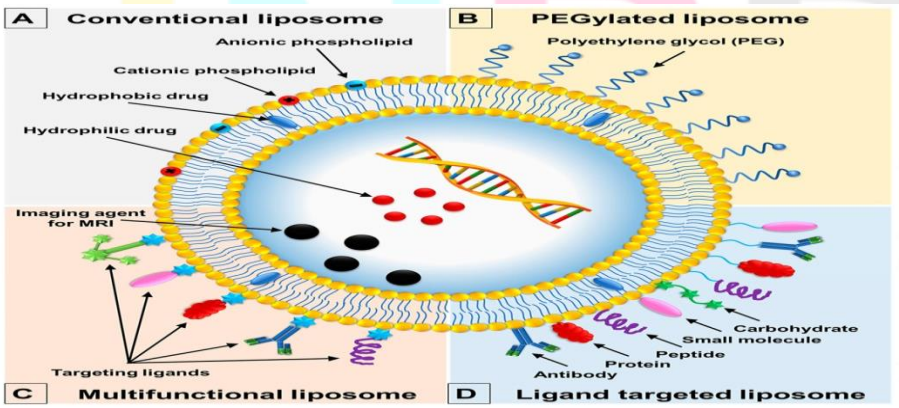


Fig 6: Liposomes

8.3.2 Solid Lipid Nanoparticles (SLNs):

They are a type of lipid-based nanoparticle used in the medical field for controlled and sustained drug delivery. Composed of solid lipids that remain solid at body temperature, SLNs encapsulate drugs, enhancing their stability and bioavailability. They offer protection against drug degradation and allow for the controlled release of therapeutic agents, making them ideal for chronic disease management. SLNs are particularly useful for delivering poorly soluble drugs and have applications in cancer therapy, oral drug delivery, and topical formulations. Their biocompatibility and low toxicity further enhance their appeal in advanced medical treatments.

Table No. 4: Summary of the SLNs for improved drug delivery.

S. No.	Drug loaded in SLN	Results
1.	Carbendazim	According to release profile, 30% of Carbendazim was released by 6th day from SLN, suggesting the sustained release
2.	Paclitaxel	After 24 hours of treatment IC50 (i.e., 50% inhibitory concentration) of Paclitaxel SLN on B16F10 cells was recorded as 200 nM and 7.7 mM approximately for dacarbazine
3.	Enrofloxacin	SLN loaded enrofloxacin accumulated 27.06–37.71 times more efficiently than free enrofloxacin. 0.24 and 0.06 μg/mL SLN loaded enrofloxacin was effective in inhibition of Salmonella CVCC541
4.	Myricetin	0.8 mg kg−1 of myricetin loaded SLN reduced focal sweat by 55%

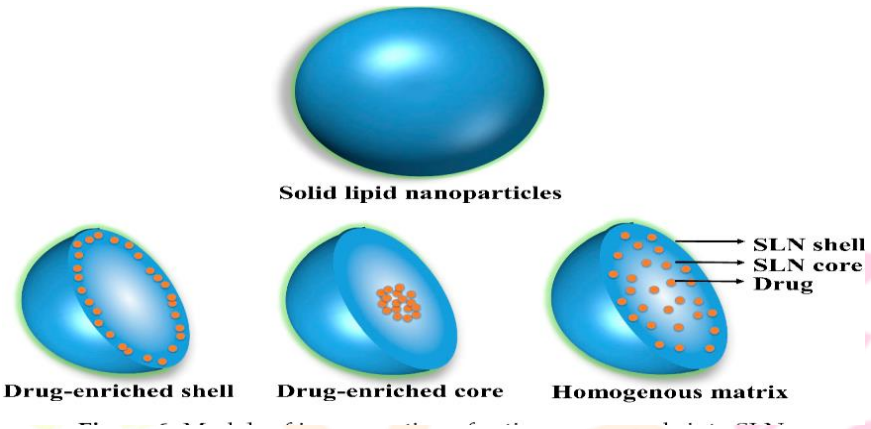
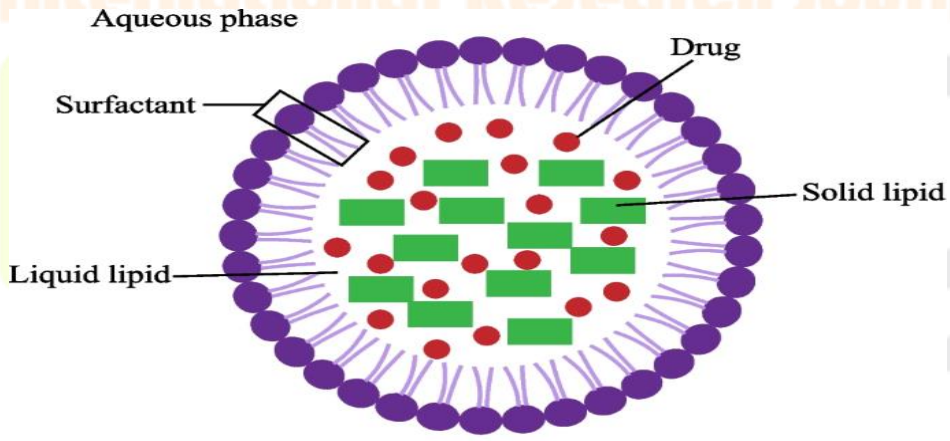


Fig 7: Solid Lipid Nanoparticles

8.3.3 Nanostructured Lipid Carriers (NLCs):

They are advanced lipid-based nanoparticles used in the medical field for enhanced drug delivery. They are composed of a blend of solid and liquid lipids, creating a more flexible and stable matrix compared to solid lipid nanoparticles (SLNs). This structure allows NLCs to accommodate higher drug loading and improve the release profiles of encapsulated drugs. NLCs are particularly effective in delivering poorly soluble drugs and are used in a variety of applications, including cancer therapy, skin treatments, and oral drug delivery. Their improved stability and biocompatibility make NLCs a valuable tool in modern medicine.



Nanostructured lipid carrier

8.4 Dendrimers:

They are highly branched, tree-like polymers with a well-defined, three-dimensional structure, making them highly versatile in the medical field, especially for drug delivery and gene therapy. Their unique architecture provides a large surface area, allowing multiple functional groups to be attached, which can be used to carry drugs, imaging agents, or targeting ligands. This multi-functionality enables dendrimers to deliver therapeutic agents precisely to target cells, reducing side effects and improving treatment efficacy.

Table 5: List of drugs loaded in dendrimers for effective drug delivery.

S. No.	Drugs	Dendrimers	Results
1.	Human epidermal growth factor receptor-2 (HER2)	Polyamidoamine	This model showed the inhibition of mammosphere formation of MDA-MB-231 and MDA-MB-231/HER2 + cells. Suggesting selective cancer killer gene Therapy
2.	Doxorubicin	L-cysteine modified G4.5 dendrimer	Under acidic condition, drug release from dendrimer was increased to approximately 16%. It inhibited the proliferation of HeLa cells in zebrafish
3.	SN-38 (anticancer drug)	L-Lysine dendrimer	Three times weekly dose of 4 mg/kg of SN-38 showed regression of almost complete tumor. Maximum weight loss in treated samples was observed as 3.6%
4.	Doxorubicin (LFC131-DOX-D4)	CXCR4 targeted dendrimers	At pH 5 faster drug release was observed compared to at pH 7.4. It binds to breast cancer cell suggesting the effective way for cancer therapy

Dendrimers are particularly valuable in cancer therapy, where they can deliver chemotherapeutic drugs directly to tumour cells, sparing healthy tissue. They are also used in gene therapy, where they can carry DNA or RNA to specific cells for genetic modification or treatment of genetic disorders. Additionally, dendrimers are explored in diagnostics and imaging due to their ability to carry contrast agents, enhancing the detection of diseases at an early stage.

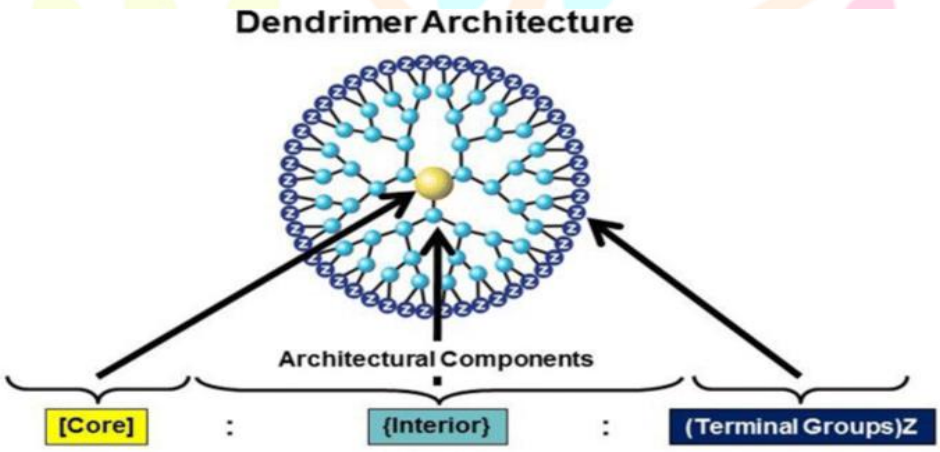


Fig 9: Dendrimers

8.5 Ceramic Nanoparticles:

Ceramic nanoparticles, such as silica and titanium dioxide nanoparticles, are utilized in the medical field for a variety of applications. Silica nanoparticles are often employed as carriers for drug delivery due to their high surface area and ability to be easily functionalized with targeting molecules. They are also used in imaging and diagnostics. Titanium dioxide nanoparticles are used in applications like photodynamic therapy for cancer treatment, where they generate reactive oxygen species upon light exposure to kill cancer cells. Both types offer biocompatibility and stability, making them valuable in enhancing therapeutic and diagnostic technologies.

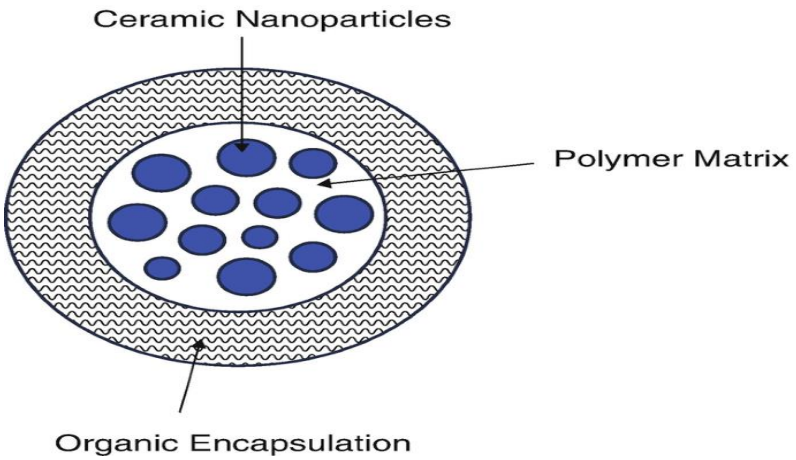


Fig 10: Ceramic Nanoparticles

8.5.1 Silica Nanoparticles:

They are widely used in the medical field for drug delivery, imaging, and diagnostics. Their high surface area and ability to be functionalized allow for targeted drug delivery and enhanced imaging. They also serve as carriers for various therapeutic agents and contrast agents in diagnostic applications. Used in drug delivery, imaging, and as carriers in diagnostics.

8.5.2 Titanium Dioxide Nanoparticles:

They used in the medical field for applications such as photodynamic therapy, where they generate reactive oxygen species to target and destroy cancer cells upon light activation. They also serve in imaging and diagnostics due to their optical properties and biocompatibility. Commonly used in sunscreens and antimicrobial coatings.

8.6 Quantum dots (QD):

Quantum dots are semiconductor nanoparticles with unique optical properties, such as size-tunable fluorescence, which make them valuable in the medical field for imaging and diagnostics. Their ability to emit light at specific wavelengths, depending on their size, allows for highly precise imaging of biological tissues. They are used as fluorescent markers in techniques like confocal microscopy and in vivo imaging, enabling researchers and clinicians to track cellular processes and disease progression with high resolution.

Quantum dots are being explored for their potential in targeted drug delivery. Their surfaces can be modified with targeting ligands to direct therapeutic agents to specific cells or tissues. It can also be utilized in biosensing, where they provide sensitive detection of biomarkers and pathogens.

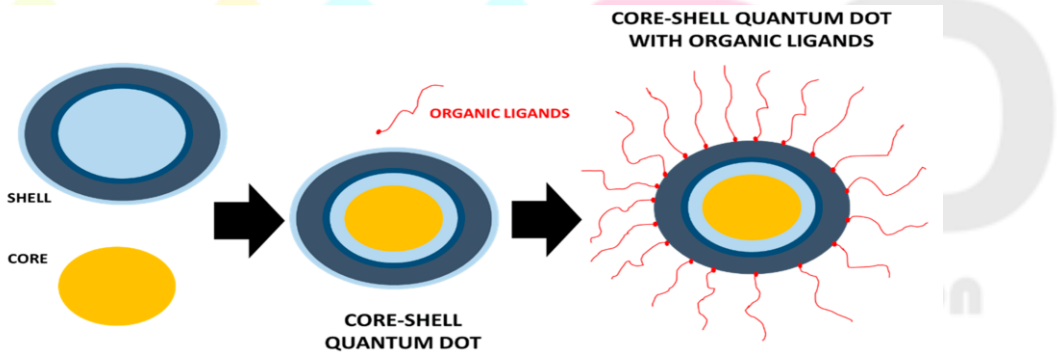


Fig 11: Quantum dots

8.7 Carbon-Based Nanoparticles:

Carbon-based nanoparticles, including carbon nanotubes, fullerenes, and graphene oxide, have significant medical applications due to their unique properties. Carbon nanotubes offer high surface area and electrical conductivity, making them useful for drug delivery, biosensing, and imaging. Fullerenes, with their spherical structure, are employed in drug delivery systems and as antioxidants. These nanoparticles are explored for their potential in cancer therapy, diagnostics, and regenerative medicine.

8.7.1 Fullerenes:

Fullerenes are carbon-based nanoparticles with a spherical structure, used in the medical field for drug delivery and as antioxidants. Their unique shape allows them to encapsulate drugs effectively, while their antioxidant properties help neutralize free radicals, potentially aiding in the treatment of oxidative stress-related diseases.

8.7.2 Carbon Nanotubes:

They are cylindrical carbon structures used in the medical field for drug delivery, biosensing, and imaging. Their high surface area and electrical conductivity enhance their ability to deliver drugs to specific cells and tissues, while also serving as sensitive detectors in diagnostic applications.

8.7.3 Graphene Oxide:

It is a carbon-based nanoparticle used in the medical field for drug delivery, tissue engineering, and biosensing. Its high surface area and functional groups enable efficient drug loading and targeted delivery, while its biocompatibility supports applications in regenerative medicine and diagnostics.

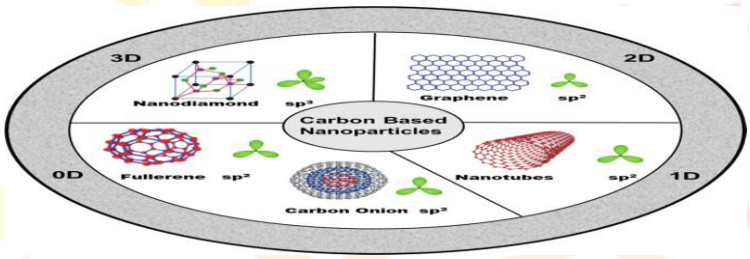


Fig 12: Carbon-Based Nanoparticles

8.8 Magnetic Nanoparticles:

Magnetic nanoparticles, primarily composed of iron oxide, play a crucial role in the medical field due to their unique magnetic properties. These nanoparticles are utilized in several applications, including magnetic resonance imaging (MRI) as contrast agents, enhancing image clarity and allowing for more precise diagnostics. Their magnetic properties also enable them to be used in magnetic hyperthermia, where they are directed to tumour sites using an external magnetic field and heated to destroy cancer cells.

They are employed in targeted drug delivery systems. By attaching drugs to these particles, they can be guided to specific tissues or cells using an external magnetic field, increasing the efficacy of treatments while minimizing side effects. They also serve as carriers in gene therapy, facilitating the delivery of genetic material to targeted cells. The ability to control the movement and accumulation of magnetic nanoparticles using magnetic fields makes them a versatile and valuable tool in advanced medical therapies and diagnostics.

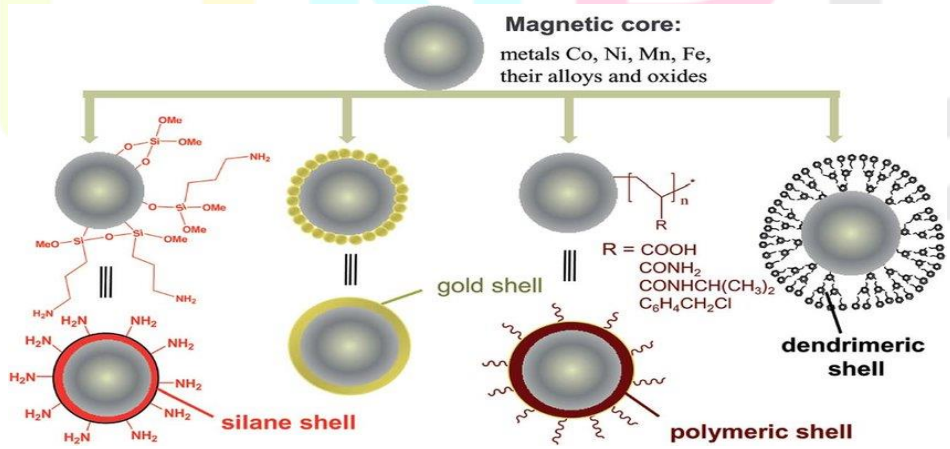


Fig 12: Magnetic Nanoparticles

8.9 Protein-Based Nanoparticles:

Protein-based nanoparticles are increasingly utilized in the medical field due to their biocompatibility and ability to be engineered for specific functions. These nanoparticles are derived from natural proteins, such as albumin, casein, or gelatine,

which can encapsulate therapeutic agents, providing a stable and controlled release. Their natural origins enhance their safety profile and reduce the risk of immune reactions.

In drug delivery, protein-based nanoparticles are employed to enhance the bioavailability and targeting of various drugs, including anticancer agents and vaccines. Their surfaces can be modified with targeting ligands to direct drugs to specific cells or tissues, improving treatment efficacy and reducing side effects. Protein-based nanoparticles are also used in imaging and diagnostics, where they can be conjugated with contrast agents for enhanced visualization. Additionally, these nanoparticles play a role in vaccine development, acting as carriers for antigens and adjuvants, thus improving immune responses.

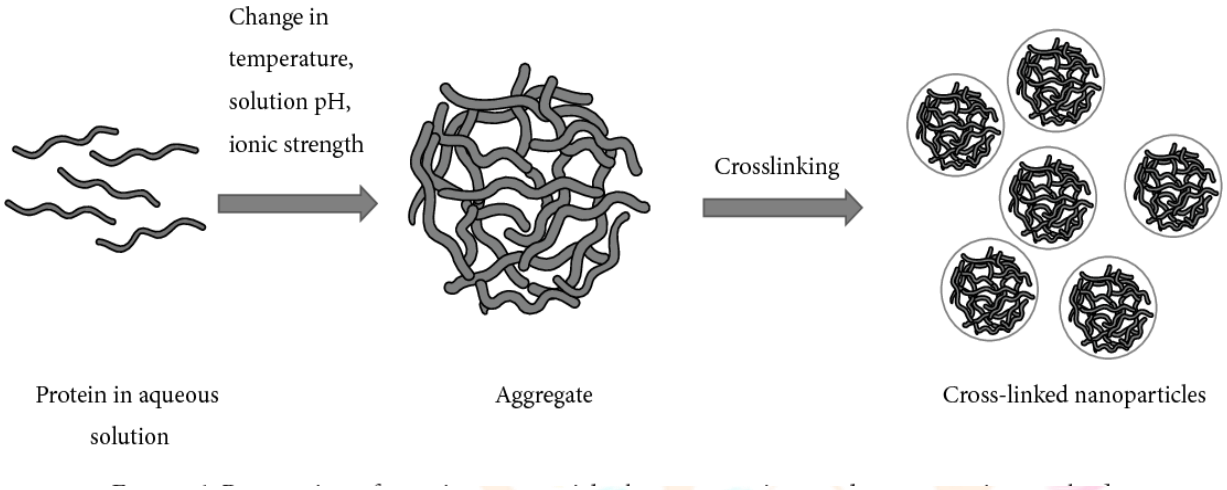


Fig 12: Protein-Based Nanoparticles

8.10 Hybrid Nanoparticles:

Hybrid nanoparticles, which combine different materials or nanoparticles into a single system, offer enhanced functionality and versatility in the medical field. These nanoparticles typically integrate organic and inorganic components, such as polymers and metals, or multiple inorganic materials, to leverage the unique properties of each constituent.

In drug delivery, hybrid nanoparticles can optimize drug loading, stability, and release profiles. For example, combining metal nanoparticles with polymeric matrices allows for controlled release and targeted delivery, enhancing therapeutic efficacy while minimizing side effects. They are used in cancer therapy, where they can be designed to deliver multiple therapeutic agents or combine therapeutic and diagnostic functions, known as theranostics. Their ability to be tailored for specific applications and combine multiple functionalities makes them a powerful tool in advancing medical technologies and improving patient outcomes.

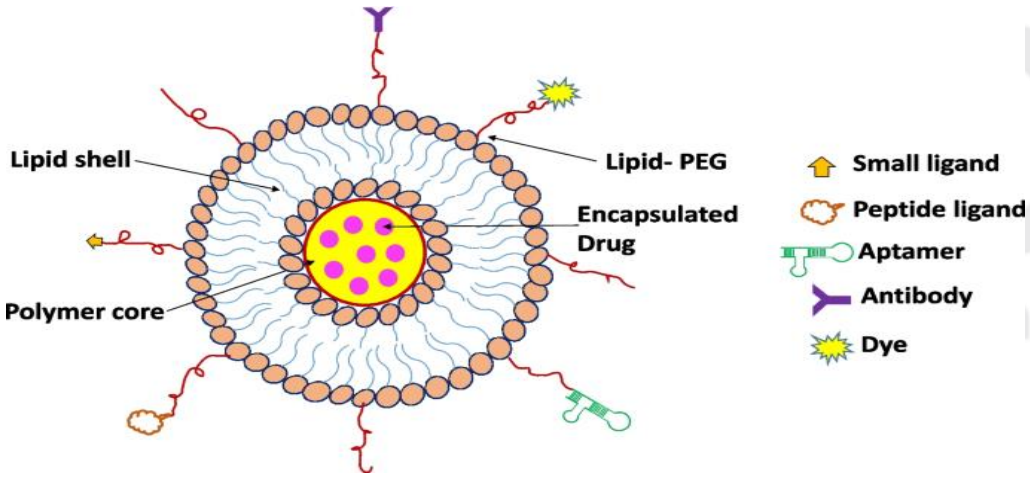


Fig 13: Lipid polymeric based Hybrid Nanoparticles

9. SMART DRUG DELIVERY SYSTEMS [3]:

Smart drug delivery systems using nanoparticles offer precise, controlled release of medications directly to target sites, enhancing treatment efficacy while minimizing side effects and improving patient outcomes. This review highlights significant smart drug delivery systems, including nucleic acid-based, exosomes, cell-based, self-nano and self-micro emulsifying drug

delivery systems, physical and chemical stimuli-responsive systems, nanoneedle patches, ultrasound-assisted delivery, microchip technology, nano and dry vaccines, and bioceramic nanoparticles.

a) **Nucleic acid-based drug delivery system:** This systems utilize DNA, RNA, or their analogs to deliver therapeutic genes or silence disease-causing genes. These systems enable precise targeting of genetic material to specific cells, offering potential treatments for genetic disorders, cancer, and other diseases at the molecular level. Recent development has led to the exploration of three pillars of nucleic acid - based drug delivery system which are DNA nanotechnology, spherical nucleic acids, and aptamers.
b) **Nanoneedle patches:** They are advanced drug delivery systems featuring tiny, needle-like structures that painlessly penetrate the skin to deliver drugs directly into targeted tissues. These patches enable precise, controlled release of medications, improving therapeutic outcomes while enhancing patient comfort and compliance.
c) **Ultrasound-assisted delivery:** It is a non-invasive technique that uses ultrasonic waves to enhance the penetration and release of drugs into targeted tissues. By temporarily altering cell membranes or activating drug carriers, this method improves the precision and effectiveness of treatments, particularly in cancer therapy and localized drug delivery.
d) **Microchip technology:** Microchip technology in medicine involves implantable devices that release precise doses of medication on a programmed schedule. These microchips can be controlled remotely, offering a reliable and convenient way to manage chronic conditions, optimize drug delivery, and improve patient adherence to treatment regimens.
e) **Nano and dry vaccines:** Nano and dry vaccines use nanotechnology to enhance vaccine stability, delivery, and immune response. Nano vaccines employ nanoparticles to target specific cells, while dry vaccines are designed for easy storage and administration without refrigeration, improving accessibility and efficacy in preventing infectious diseases.

10. METHODS OF PREPARATION OF NANOPARTICLES [1]:

Nanoparticles can be prepared from a variety of materials such as proteins, polysaccharides and synthetic polymers. The selection of matrix materials is dependent on various factors which include:

a. Size of nanoparticle required

b. Inherent properties of the drug, e.g., aqueous solubility and stability

c. Surface characteristics such as charge and permeability

d. Degree of biodegradation, biocompatibility and toxicity

e. Drug release profile desired

f. Antigenicity of the final product.

The various methods are as follows:

10.1 Emulsion Polymerization: This process involves the polymerization of monomers in an aqueous emulsion, forming nanoparticles with controlled size and composition. During emulsion polymerization, monomers are dispersed in water with the help of surfactants, creating micelles that serve as reaction sites. As polymerization proceeds, monomers are incorporated into these micelles, resulting in the formation of polymeric nanoparticles. This method offers precise control over particle size, distribution, and surface properties. Emulsion polymerization is valuable for producing nanoparticles with high stability and uniformity, making it suitable for drug delivery systems, imaging agents, and other biomedical applications where consistency and control are crucial.

10.2 Desolvation method: The desolvation method is a technique used for preparing nanoparticles, particularly in the pharmaceutical and biomedical fields. This process involves the formation of nanoparticles by inducing the desolvation of a polymer or drug from a solvent. Typically, a polymer or drug is dissolved in a solvent to create a solution. By adding a non-solvent or adjusting conditions such as temperature, the solubility of the polymer or drug decreases, leading to its precipitation as nanoparticles. The resulting nanoparticles are then stabilized through various methods, such as the addition of stabilizers or surfactants. This method allows for precise control over particle size and distribution and is commonly used to produce nanoparticles for drug delivery, targeting, and imaging applications.

10.3 High Pressure Homogenization: High pressure homogenization is a technique used to prepare nanoparticles by applying intense pressure to disperse and break down materials into nanoscale particles. In this method, a material—typically a suspension of drug or polymer—is forced through a narrow gap under high pressure. The extreme shear forces and cavitation

created in the homogenizer break the particles into smaller sizes, often down to the nanoscale. This method is effective for producing uniform nanoparticles with controlled size and distribution. It is widely used in pharmaceuticals for drug delivery systems and in biotechnology for creating nanoparticles with specific properties for imaging and therapeutic applications.

10.4 Controlled Gellification Method: It is used for preparing nanoparticles by leveraging the gelation of polymers to form nanoparticles. In this process, a polymer solution is mixed with a gelling agent or subjected to specific conditions (such as temperature or pH) that induce gelation. As the polymer gel forms, it is then broken down into nanoparticles through mechanical or chemical processes. Controlled gellification is particularly useful for creating nanoparticles with specific drug release profiles and stability. It is commonly employed in drug delivery systems and tissue engineering, providing a versatile approach to fabricating nanoparticles with tailored properties for various biomedical applications.

10.5 Controlled Nanoprecipitation without Surfactants: It is a method for preparing nanoparticles by inducing the precipitation of a solute from a solution without the use of surfactants. In this process, a solution of the polymer or drug is rapidly mixed with a non-solvent, causing the solute to precipitate out as nanoparticles. The key to this method is controlling the mixing conditions, such as flow rates and temperatures, to achieve uniform particle size and distribution. This method is particularly useful for fabricating nanoparticles for drug delivery systems, where maintaining biocompatibility and reducing potential interactions with biological systems are critical.

11. EVALUATION OF NANOPARTICLES:

Evaluation of nanoparticles involves assessing their size, shape, surface properties, drug loading efficiency, stability, and biocompatibility to ensure their effectiveness and safety for targeted drug delivery and therapeutic applications.

11.1 Size Distribution:

Size distribution of nanoparticles is typically evaluated using Dynamic Light Scattering (DLS), which measures the scattering of light by nanoparticles in suspension to determine their size and size distribution. Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM) can also provide high-resolution images and accurate size measurements. These methods help assess the uniformity and stability of nanoparticle formulations, ensuring consistency in their performance and application. Measurement of nanoparticle diameter and its distribution, typically using techniques such as dynamic light scattering (DLS) or scanning electron microscopy (SEM).

11.2 Surface Charge (Zeta Potential):

Surface charge of nanoparticles, quantified as zeta potential, is measured using electrophoretic light scattering. In this method, nanoparticles are dispersed in a liquid and subjected to an electric field. The movement of nanoparticles under this field is tracked to determine their charge. The zeta potential indicates the stability of the nanoparticle dispersion, with higher absolute values suggesting better stability due to electrostatic repulsion between particles.

11.3 Drug Loading and Encapsulation Efficiency:

Drug loading and encapsulation efficiency are assessed by quantifying the amount of drug associated with nanoparticles. Typically, the nanoparticles are separated from unencapsulated drug using techniques like ultrafiltration or centrifugation. The amount of drug loaded is measured through analytical methods such as high-performance liquid chromatography (HPLC) or UV-visible spectroscopy. Encapsulation efficiency is calculated as the ratio of the amount of drug loaded to the total amount of drug used in the formulation.

11.4 Drug Loading and Encapsulation Efficiency:

Drug loading and encapsulation efficiency are evaluated by first separating nanoparticles from unencapsulated drug using methods like ultrafiltration or centrifugation. The drug content in the nanoparticles is then quantified using techniques such as high-performance liquid chromatography (HPLC) or UV-visible spectroscopy. Drug loading refers to the amount of drug per unit weight of nanoparticles, while encapsulation efficiency is calculated as the percentage of drug encapsulated relative to the total drug initially used.

11.5 Targeting Efficiency:

Targeting efficiency is evaluated by assessing the ability of nanoparticles to selectively bind and accumulate in specific target cells or tissues. This is often done using techniques such as fluorescence or radiolabeling to track nanoparticles in vitro and in vivo. Additionally, assays like flow cytometry or confocal microscopy can measure the extent of cellular uptake and binding to targeted receptors, providing insights into the effectiveness of targeting strategies.

12. APPLICATIONS OF NANOPARTICLES:

1. **Nanoparticles for Gene delivery:** Nanoparticles used for gene delivery include lipid-based nanoparticles, such as liposomes and solid lipid nanoparticles, which encapsulate genetic material and facilitate its entry into target cells. Polymeric nanoparticles and dendrimers can also carry and protect DNA or RNA while enhancing cellular uptake. Additionally, viral nanoparticles, engineered for gene delivery, can effectively transfer genetic material into cells.
2. **Tumor targeting using Nanoparticulate delivery system:** It involves designing nanoparticles to specifically accumulate in tumour tissues. This is achieved through modifications such as surface ligands or antibodies that bind to tumour-specific receptors, exploiting the enhanced permeability and retention (EPR) effect. Nanoparticles can also be engineered to respond to tumour microenvironment conditions, such as pH changes, facilitating targeted drug release.
3. **Anti-Microbial Techniques:** Nanoparticulate delivery systems utilize antimicrobial nanoparticles, such as silver and zinc oxide, to combat infections. These nanoparticles exhibit potent antimicrobial activity by releasing metal ions that disrupt microbial cell membranes or inhibit essential microbial processes. Their high surface area enhances interaction with pathogens.
4. **Cell Repair using Nanoparticulate delivery system:** Nanoparticulate delivery systems aid in cell repair by delivering therapeutic agents, growth factors, or genetic materials directly to damaged cells. Nanoparticles can be engineered to release their payload in response to specific stimuli or environmental conditions, promoting cell regeneration and repair. They can support tissue engineering by providing structural support and enhancing cell adhesion, proliferation, and differentiation.
5. **Nanoparticles for drug delivery into the brain:** Nanoparticles for drug delivery into the brain often utilize strategies to cross the blood-brain barrier (BBB). This includes using lipid-based nanoparticles, polymeric nanoparticles, or those with surface modifications that facilitate BBB penetration. Techniques such as receptor-mediated transport, active targeting or exploiting transient disruptions in the BBB are employed.

13. ETHICS AND REGULATORY AFFAIRS IN NANO-DRUG DELIVERY SYSTEM [3]:

Ethics and regulatory affairs in nano-drug delivery systems are critical as these technologies raise unique challenges in safety, efficacy, and environmental impact. The potential for unintended side effects, such as toxicity or unforeseen interactions at the nanoscale, necessitates rigorous evaluation. Regulatory bodies like the FDA (USA) and EMA (Europe) have established guidelines for nanoparticle-based drugs, but global harmonization remains complex due to differing standards. Ethical considerations include informed consent, where patients must fully understand the novel risks associated with nanomedicines. Furthermore, there are concerns about long-term environmental impacts and the equitable access to advanced nano-therapies. Continuous monitoring, transparent communication, and international collaboration are essential to address these ethical and regulatory challenges while fostering innovation in the field. Compliance with Good Manufacturing Practices (GMP) and thorough clinical trials are essential to meet these standards. Balancing innovation with patient safety and public health is key in the ethical and regulatory oversight of nano-drug delivery systems.

14. FUTURE PROSPECT OF NANO-BASED FORMULATION:

Nano-based formulations in medicine hold immense potential for revolutionizing treatment by enabling targeted drug delivery, reducing side effects, and enhancing therapeutic efficacy. Future advancements could lead to personalized medicine, improved treatment for complex diseases, and more effective vaccines, paving the way for significant breakthroughs in healthcare.

a) **Developing drug delivery systems for future viruses:** Developing drug delivery systems for future viruses using nano-based formulations involves creating adaptable and highly targeted therapies that can respond to emerging viral threats. These systems must be designed to rapidly deliver antiviral agents with precision, enhance immune responses, and navigate complex biological barriers.

b) **Safety and efficacy of drug:** Ensuring safety in nano-based formulations involves rigorous testing for toxicity, long-term effects, and potential interactions. Comprehensive risk assessments, standardized protocols, and stringent regulatory guidelines are essential to safeguard patient health and ensure that these advanced therapies are both effective and safe for clinical use.

c) **Creating symbiotic drug delivery systems:** Creating symbiotic drug delivery systems in nano-based formulations involves designing nanoparticles that work harmoniously with the body's biological processes. These systems can enhance drug efficacy by mimicking natural cellular functions or interacting synergistically with physiological mechanisms.

d) **Gender-sensitive drug delivery systems:** Gender-sensitive drug delivery systems in nano-based formulations aim to tailor treatments based on gender-specific physiological and hormonal differences. Future advancements could involve designing nanoparticles that adjust drug release and targeting strategies according to gender-related factors, enhancing efficacy and minimizing side effects.

e) **Designing more environmentally friendly drug delivery methods:** Designing more environmentally friendly drug delivery methods in nano-based formulations involves creating biodegradable and non-toxic nanoparticles that

minimize environmental impact. By prioritizing green chemistry and reducing waste, these innovations can improve the sustainability of medical treatments while maintaining efficacy and safety, contributing to a more eco-conscious approach to healthcare.

f) **Nanodrug delivery systems for anti-cancer agents:** Many researchers have used different approaches and techniques for formulating nanoparticles for anti-cancer agents. Some of these studies along with their prominent findings are mentioned here.

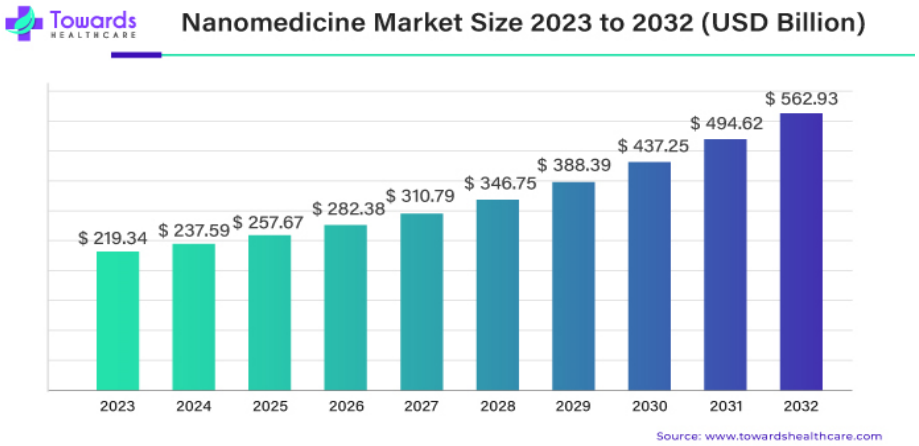


Fig 14: Nanomedicines Market Graph

TABLE 1: Different types of anti-cancer agents and their mode of action against cancer cell

HYDROPHOBIC PROPERTIES:

Anti-cancer agents	Techniques	Mode of Findings	Findings
Paclitaxel	Albumin-bound paclitaxes 1 (ABI-007, Abraxane®, Abraxis BioScience and Astrazeneca)	Natural carrier of endogenous hydrophobic molecules such as vitamins, hormones and other water-insoluble plasma substances.	Help endothelial transcytosis of protein-bound and unbound plasma constituents.

HYDROPHILIC PROPERTIES:

Anti-cancer agents	Techniques	Mode of Findings	Findings
Pluronics	Incorporated with doxorubicin and other anticancer agents	Interact with multidrug resistance (MDR) cancer cells	Drastic sensitization of cancer cell

14.1 Some Indian Technologies [1, 3]:

a) First produced smart hydrogel nanoparticles for drug delivery applications (US Patent 5847111)
b) Tumour Targeted Delivery of Taxol using nanoparticles (US Patent 6322817)
c) Inorganic Nanoparticles as non-viral vectors for targeted delivery of genes (US Patent 6555376); Technology transferred to a California based Pharm Com
d) Once in 48 hours dose ophthalmic delivery (US Patent 6579519) (Another improved formulation patent on ophthalmic gels is being submitted in India)
e) Oral Insulin Delivery (Patent Pending)

15. CONCLUSION:

Drug delivery systems are crucial for treating a range of health issues. In these systems, the drug is typically carried by nanocarriers, which bind to specific receptors on the target cells. After binding, the nanocarriers are internalized through endocytosis. Once inside, the drug is released into the endosomes. Targeted drug delivery can also occur through alternative methods, such as using specialized linkers that bind the drug directly to specific cellular targets or encapsulating the drug within

nanocarriers that release it only under certain conditions, like changes in pH or temperature. These methods ensure that the drug is delivered precisely where it's needed, enhancing its effectiveness and minimizing side effects.

This review examines both traditional drug delivery systems and their advantages and limitations. These innovative systems, including nucleic acid-based, cell-based, self-nano and self-micro emulsifying, and stimuli-responsive methods, address the shortcomings of conventional systems. They enhance drug bioavailability, stability, absorption, and controlled release, offering more effective treatment options for various health conditions. Recent advancements have led to the development of novel drug delivery systems like nanoneedle patches, ultrasound-based delivery, and microchips. These cutting-edge technologies are being extensively researched for their potential to achieve precise and controlled drug delivery, promising significant improvements in targeting and effectiveness for future treatments.

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