

I] Introduction to Nano-biotechnology.

Nanobiotechnology -

- Nanotechnology merges nanotechnology [manipulating matter at the atomic/molecular scale] with biotechnology [using living systems] to create tools & materials for life science applications, focusing on the 1-100nm range
- It involves using nanoparticles for targeted drug delivery, advanced diagnostics (biosensors, imaging), tissue engineering & gene therapy essentially making 'miniaturized biotechnology' to study, repair & enhance biological systems for improved health, environmental & agricultural uses

[Nanotechnology + Biotechnology]

Nanobiotechnology]

$$1\text{m} = 10^9 \text{ Nanometer}$$

$$1\text{nm} = 10^{-9} \text{ m}$$

(Nanometer is one billionth of meter.)

- An individual atom = 0.25 nm

- i) Proteins $\rightarrow$ 1-20 nm
- ii) Ribosome $\rightarrow$ 2-4 nm
- iii) Virus $\rightarrow$ 100 nm
- iv) Bacterium $\rightarrow$ 1000 nm

- Nanotechnology can increase the surface area of material, that increase the interaction of material with other materials

History -

→ Richard Feynman → Gives the ideas and (1959)

concept of nanotech not used the term 'nanotechnology' (Father of nanotechnology).

- During 1980,

scientists & engineers were also to see & manipulate atom after discovery of Scanning tunneling microscope.

- 1986 → Binnig & Rohrer

↓
Nobel prize in physics

↓
for inventing scanning tunneling microscope.

- 1990 - → discovery of carbon nanotubes
1991

- 1997 → Design of nanorobotics

- In traditional system of medicine Swarna Bhasma (colloidal gold nanoparticles) were used in therapeutics.

- Scope in biotech field

→ ecosystem remediation by using nanoparticles

- use of nanosensors to increase agriculture productivity.
- use of nanoparticles to provide protection from disease.
- drug delivery system.

* Introduction to nanoscale -

- The study of phenomena at the nanoscale is known as nanoscience.

$$1 \text{ nm} = 10^{-9} \text{ m}$$

- at least one dimension less than 100 nm could be considered a part of nanoscience.

- At the nanoscale

- materials show unique physical, chemical & biological properties

- Properties can differ from the same material at bulk scale.

- Surface area to volume ratio is very high.

eg. gold nanoparticles - 10-50 nm

- At the nanoscale, the properties of a material are affected more by,

- Surface area

- arrangement of atoms

- quantum effects

- Nanoparticles occur naturally too. many cosmic, geological, climatic, & biological processes produce them. even the size of many viruses falls in the nanoscale range.

- Inside the human body, many important activities happen at the nanoscale →

- 1) Proteins act like tiny machines inside cells
- 2) Motor proteins help in movement & transport
 - myosin helps muscles contract
 - kinesin carries materials inside cells
 - dynein moves materials toward the nucleus & helps in the movement of cilia & flagella.

- Important cell processes are also done by nanoscale machines.

i) DNA polymerase copies DNA

ii) RNA polymerase makes RNA

iii) Ribosomes make proteins.

iv) spliceosome removes unwanted parts from RNA.

- These natural nanoscale machines are much more complex & efficient than any machines made by humans.

* Nanomaterials -

- The quantum characteristics of the material can vary at the nanoscale.

- Nanomaterials are substances created utilising the principles & processes of nanotechnology. They have properties that fall between those of macroscopic solids & atomic systems.

- At the nanoscale, materials show special optical, electrical, mechanical & quantum properties.
- Nanomaterials can be formed naturally, intentionally by humans, today nanomaterials are commercially produced & used in many products.
- Properties of nanomaterials
 - 1) very large surface area when the size becomes very small, the surface area increases. this allows atoms & molecules to interact more easily with each other.
 - 2) Better & new properties due to increased interactions, nanomaterials show new surface, electronic & quantum effects, which change their optical, electrical & magnetic behavior.
 - 3) small amount gives big effect even a very small quantity of nanomaterial can greatly improve the properties of other material
 - 4) High reactivity -
Nanomaterials are more reactive because their surface area to volume ratio is high.
 - 5) Properties depend on size & shape, their size, shape, crystal structure, stability,

and chemical composition affect how they behave

6) change in structure -

Nanomaterials can change their crystal structure when they interact with water / other liquids -

7) Aggregation behavior -

whether nanomaterials stick together or remain separate depend on their size, composition & surface charge

8) Effect of surface coating.

The magnetic & chemical properties of nanomaterials change when their surface is coated.

9) Formation of reactive oxygen species (ROS) when nanomaterials come in contact with oxygen / ozone, reactive oxygen species may be formed.

10) Forces at nanoscale.

At nanoscale, particles interact through van der Waals forces, polar forces or covalent bonds.

11) surface modification

The surface properties of nanomaterials can be changed using polyelectrolytes.

• classification of Nanomaterials -

A] Nanomaterials can be classified on the basis of their dimensions.

- i) 0D $\rightarrow$ less than 100nm
very small in length, width & height
eg. gold nanoparticles, & silver
- ii) 1D $\rightarrow$ larger, while the other two are in the nanoscale
long & thin in shape.
eg. Nanowires, nanorods, nanotubes
- iii) 2D $\rightarrow$ two dimensions are in the nanoscale
thickness is very small, but length & width are larger.
eg. nanocoatings, nanolayers, nanofilms
- iv) 3D $\rightarrow$ all three dimensions are outside the nanoscale
- these are also called bulk nanomaterials

B] classification based on chemical composition

i) organic Nanomaterials

- these are carbon-based nanomaterials
- They are useful in biomedical applications because of strong chemical bonds.
- uses
- help in regeneration of bone, cartilage, skin & dental tissues.

- widely used in dentistry, such as,
 - Implants
 - Root canal treatment
 - Gum treatment
 - wound healing
- very useful in drug delivery.
- can carry medicines, proteins & DNA inside the body.
- eg. micelles, liposomes, Nanogels, dendrimers

ii) Inorganic Nanomaterials -

- made from metals, metal oxides, ceramics, & some non-metals.
- They have special optical, magnetic, electrical & fluorescent properties.

uses

- Bioimaging
- Targeted drug delivery
- cancer treatment
- other technological applications

iii) Hybrid Nanomaterials -

- Made by combining organic and inorganic materials
- They contain two or more different components.
- The final material has better & new properties than individual materials.

c) classification of nanomaterials based on physical & chemical properties

- Nanotechnology is the study & use of very tiny particles.

- It is used engineering, material, science, physics, chemistry & biology.
- Nanoparticles help connect the world of atoms & molecules with the world of visible objects.
- Traditional knowledge
 - In Ayurveda, Bhasma is believed to contain naturally formed nanoparticles.
 - The idea of using nanometals is mentioned in Charaka Samhita.
- metal nanoparticles & eg. for use in biomedical use
 - eg. Silver nanoparticles (AgNP)
 - Gold -||- (AuNP)
 - copper oxide -||- (CuO NP)
 - zinc oxide -||- (ZnO NP)
 - selenium -||- (SeNP)
 - Iron oxide -||-
- how are nanoparticles made?
 - by biological methods using plants / microbes
 - by chemical methods
 - by physical methods
- application of nanoparticles
 - energy storage (batteries)
 - pharmaceutical industry
 - medical uses, especially cancer treatment.

- drug delivery systems
- vaccines & gene therapy.
- Sunscreens
- Rechargeable batteries

2] quantum dots.

- quantum dots are very tiny nanocrystals.
- size range 2-10 nm
- They are ~~small~~ semiconductor particles
- have both optical (light related) & electrical properties.
- widely used in, medical treatments, Bioimaging, electronic displays (LEDs, screens).
- They can be made from diff materials such as zinc sulfide, lead sulfide, zinc selenide, cadmium selenide & indium phosphide.
- In the human body, they can be coated with polymers to prevent toxic substances from entering cells.
- They can be used in personalized medicine, especially for cancer treatment.
- also used in solar cells, LED displays, photodetectors, photocatalysts.

3] carbon Nanotubes (CNTs) -

- They are cylindrical (tube shaped), made of carbon.
- They are special forms (allotropes) of carbon
- Types
 - i) single wall carbon nanotubes (SWCNTs) -
 - made of a single layer of carbon atoms.

- Their size is about one nanometre.
- They lie betⁿ fullerene structure & flat graphene.

ii) Multi-wall - " - (MW/CNTs) -

- made of many layers of carbon nanotubes placed one inside another.
- The layers are held together by weak van der Waals forces.
- Properties
 - very good electrical conductivity
 - very high tensile strength (very strong)
 - excellent thermal conductivity.
- Uses → electronics, optics, composite materials

4] Nanocomposites -

- A nanocomposite is a solid material made of 2 or more materials, where at least one component has a size less than 100 nm.
- the aim of nanocomposites is to create materials with, better strength, more flexibility, improved properties.
- eg. porous materials, gels, colloids, copolymers
- why nanocomposites are better.
 - ↳ - They have a very high surface-to-volume ratio.
 - Nanoparticles stick well to the main material.

- This gives better performance than normal composites.

- application $\Rightarrow$ construction, Automobile-industry, advanced materials.

5] Nanomembranes -

- Nanomembranes are very thin membranes with thickness less than 100 nm.
- They are usually made from organic polymers mixed with silica nanoparticles.
- These membranes have tiny holes (Pores).
- Small molecules pass easily, while bigger molecules pass less, depending on their size.
- They are often made using a layer-by-layer method.
- This method helps in precise control of membrane structure.
- diff materials can be added to improve properties.
- Improved properties $\Rightarrow$
 - mechanical properties (strength)
 - optical properties
 - electrical p₄₁₁
 - added materials may include nanoparticles & nanotubes.

6] Nanopolymers -

- Nanobiopolymers are natural / bio-based polymers at the nanoscale.
- eg. Nanocellulose, Nanostarch, Nanochitin, Nanosilk.

- These are made by plants, animals or microbes.
- why are nanobiopolymers important?
 ⇒ They are eco-friendly, biodegradable, biocompatible, sustainable.
 ⇒ They are better than petroleum-based polymers because they do not harm the environment.

↳ uses of nanopolymers in medicine

- Tissue engineering, Regenerative medicine, Targeted drug delivery to specific organs
- Gene therapy (DNA delivery)
- delivery of proteins, peptides & genes
- oral drug delivery

↳ They also,

- Improve drug absorption
- Increase effectiveness of medicines
- are safe for cells & tissues.

↳ Environmental & economic benefits

- support green chemistry.
- Improve bio-economy
- Reduce pollution.

↳ Importance of nanotechnology

- Helps create lighter, safer & stronger materials.
- used in
 - vehicles, airplanes, spacecraft, ships.
 - plays a major role in material science, biology, chemistry & physics.

B] Nanoscale bioassemblies -

- Nanoscale bioassemblies are tiny structures formed when biological molecules join together by themselves at the nanoscale.

↳ what is self-assembly?

- molecules arrange themselves naturally
 - No external force is needed
- Held together by weak interactions like Hydrogen bonds, electrostatic forces, van-der Waals forces.
 - eg. lipid bilayers (cell membranes), protein complexes, DNA double helix, virus capsids, micelles, Liposomes.

↳ why are they important?

- They are biocompatible & safe
- can carry drugs or genes
- mimic natural biological systems.

↳ Applications -

- drug delivery systems
- Gene therapy
- Bioimaging
- Tissue engineering
- Biosensors

↳ Advantages

- precise structure
- eco-friendly
- efficient & targeted action

c] Liposomes, viruses, DNA, polysaccharides & proteins

- Nanoscale bioassemblies are nanomaterials made from biological building blocks.

↳ special features of bio-nanoparticles

- These features make them better than artificial nanoparticles.
- well organised nanoscale structure
- uniform size & shape
- 3D structure formed at atomic level.
- can be produced economically on a large scale.
- Genetic information allows easy control of composition & surface properties using recombinant technology.

• Liposomes -

- Liposomes are tiny spherical vesicles made of lipid bilayers.
- They have a water-filled inner core.
- Types → (i) Unilamellar vesicles
 - single lipid layer
 - size = 50-250 nm
- (ii) Multilamellar vesicles
 - multiple lipid layers
 - size = 500-5000 nm.
- liposome were discovered by Bangham (1995).
- initially used as models of cell membranes.
- uses of liposomes → drug delivery, Medical imaging.

- used as nanoscale reaction vessels due to their aqueous core.

- drug loading in liposomes.

 - Hydrophobic drugs → inserted into lipid layer

 - Hydrophilic drugs → trapped inside watery core

- Drug can also be attached to the surface, chemically bonded to liposomes.

- Advantages of liposomes →

 - low toxicity

 - Biodegradable

 - Biocompatible

 - flexible size + surface modification

 - Highly versatile

- Multifunctional Liposomes -

 - scientific studies show that liposomes are effective in cancer treatment.

- Doxil is well known example of a liposomal drug that contains Doxorubicin (Dox)

- Stealth liposomes

 - In Doxil, the outer surface of the liposome is coated with PEG (polyethylene glycol)

 - this coating helps the liposome stay longer in the blood, escape the immune system

 - such liposomes are called stealth liposomes.

- Limitations of conventional liposomes

 - They have short half life in blood

 - Poor control over drug release

 - Low stability

↳ Advanced liposome technology

- Scientists from material science, pharmacology & cell biology work together to improve liposomes.
- Drug release can be controlled using external or environmental triggers like,
 - pH
 - temperature
 - magnetic field
 - electromagnetic radiation / radio waves
- this helps in, local drug delivery, sustained drug release over long time.

eg. Thermodox

- Thermodox is a temperature-sensitive liposome carrying Dox.
- It is being studied for treatment of liver cancer (hepatocellular carcinoma).
- Therapeutic & diagnostic uses -
 - Liposomes are useful due to high therapeutic efficiency.
 - Good physical & chemical adaptability.
- They can be used in, diagnosis, treatment.
- Treatment can be customized for each patient.

↳ Theranostic liposomes

- Some liposomes can be used for both diagnosis & therapy (theranostics).

- These are still in Preclinical development.
- In one method
 - ↳ quantum dots (QDs) are placed in the lipid layer.
- ~~Thin~~ The inner cavity is filled with Dox.
- Drug loading efficiency is about 97%.

2] Nucleic acid based nanoassemblies (DNA) -

- DNA is very small in size, so it is useful in nanotechnology.
- DNA has a persistence length of ~ 50 nm, making it suitable for building nanoscale structure.
- DNA has a regular repeating structure of about 3.4-3.6 nm & a diameter of about 2 nm.
- because DNA base pairs bind specifically, scientists use this property to build DNA nanostructures.
- In 2004, Shih & colleagues folded a single-stranded DNA (1.7 Kb long) into an octahedral shape using a simple heating & cooling (denaturation-renauration) process.
- DNA origami is a popular & flexible method to make DNA nanostructures.
- It was first introduced by Paul Rothemund in 2006.
- In this method, A long single-stranded DNA is used as a base.

- many short complementary DNA strands called 'staples' are attached to it.
- The mixture is heated & then cooled to room temperature.
- this allows DNA to fold into different shapes, such as stars, smiley faces other complex patterns.
- a computer program is used to design the sequences of the staple strands.
- In 2009, Douglas et al improved DNA origami to make three-dimensional DNA shapes. (3D)
- This made DNA useful as a nanomaterial. For bottom-up manufacturing in synthetic electronics.
- Andersen et al (2009) created a DNA box with a programmable lid, ability to sense & respond.
- In 2012, Douglas et al. developed a DNA nanorobot that can carry antibody fragments, transport gold nanoparticles, target specific cells.

↳ Medical applications ⇒

- These DNA nanostructures are very useful in cancer treatment.
- In gene therapy, DNA nanoparticles are used instead of viral vectors because they are safer, they avoid immune system.

attack

- they are easier to produce on a large scale.
- they have better storage stability.

↳ limitations + future scope

- DNA delivery systems are safer & flexible, but they are less efficient than viruses in delivering genes.
- In the future
 - DNA delivery systems may include virus-like mechanisms.
 - this will improve their performance while remaining safe.

3] virus-like particles - (VLPs)

- VLPs are made from viral capsid proteins.
- they do not contain DNA or RNA, so they cannot cause infection.
- because they lack genetic material, VLPs are safe & do not revert to harmful viruses.

↳ Important features of VLPs

- They have.
 - strong protein shells
 - Nano-size
 - uniform shape & size
 - well defined geometry.
- These properties make them ideal for nanotechnology applications.

- scientists know the atomic structure of many viruses
- this allows $\rightarrow$ modification of amino acids on the capsid surface
 - $\Rightarrow$ easy bioconjugation (attaching other molecules)
- site-directed mutagenesis helps add amino acids like - lysine, cysteine on the surface of VLPs.

↳ Bioconjugation of VLPs

- bioconjugation is done using chemical linkers (homo or hetero - bifunctional)
- Lysine & cysteine residues are easy to access, making attachment simple.
eg. foreign proteins were attached to cowpea Mosaic virus (CPMV) using chemical linkers

↳ Custom-designed VLPs

- Researchers developed methods to attach specific ligands to VLP surfaces.
- this is done using $\rightarrow$ cell-free protein synthesis
 - $\rightarrow$ one-step conjugation methods.
- These custom VLPs can be used in, vaccines, diagnostics, disease treatments, nanotechnology.

↳ VLPs with Fullerenes (C₆₀)

- Fullerenes (C₆₀ or buckyballs) have poor water solubility

- VLPs help by
 - a) acting as hydrophilic carriers, increasing water compatibility.
 - b) serving as a template to arrange many C₆₀ molecules.
- C₆₀ - VLP hybrids show promise in light activated cancer therapy.

↳ cancer & immunotherapy applications -

- VLPs can produce strong anti-tumor immune responses.
- ↳ studies showed
 - single injection of modified VLPs produced powerful anti-tumor effects.
- VLPs have been tested in melanoma (skin cancer) treatment.
- Alphavirus - based VLPs carrying tumor antigens like tyrosinase were used successfully.

↳ TRP-2 & VLP-based cancer vaccines

- Tyrosinase related protein - 2 (TRP-2) is a very strong antigen (substances that trigger immunity)
- when TRP-2 was delivered using virus replicon particles (VRP-TRP-2)
 - specific antibodies were produced
 - cell-mediated immunity was activated
 - A good therapeutic effect was seen against cancer

↳ VLP-based vaccines -

- The first cancer preventing vaccines are based on VLPs.
- eg. HPV vaccine → prevents HPV-related liver & cervical cancer.

- HBV vaccine $\rightarrow$ prevents hepatitis-B-related liver cancer.

↳ VLPs are safe because they do not contain viral DNA or RNA.

4] Ferritin Protein cages-

- Ferritins are globular proteins that store iron safely in the body.
- They are found in microorganisms, plants, & animals.
- their main role is iron homeostasis (maintaining proper iron levels).

↳ Structure of ferritin-

- Ferritin proteins self-assemble into hollow cages.
- Maxi-ferritin
 - made of 24 identical protein subunits
 - forms a spherical structure.
- size $\rightarrow$ inner cavity $\approx 8\text{ nm}$
 $\rightarrow$ outer diameter $\approx 12\text{ nm}$.
- Iron particles stored inside are very small (1-2 nm).

↳ Types of ferritin hollow cages

- i) Maxi-ferritin - 24 subunits
- ii) Mini-ferritin - 12 subunits, tetrahedral symmetry.

↳ Ferritin in nanotechnology

- Ferritin cages act as nano-containers for chemical reactions.

- They are used to produce bio-inorganic nanomaterials with controlled size.
eg. Iron sulfide nanoparticles produced inside ferritin cages.

↳ Metal nanoparticle formation-

- making nanoparticles with highly oxidized metal ions is difficult.
- Scientists showed that light (photo-induced methods) can help form stable nanoparticles inside ferritin.
- Nanoparticles made include -
 - Iron oxyhydroxide
 - Titanium
 - Europium

↳ Advanced ferritin Engineering-

- Metal-binding peptides can be inserted inside ferritin cages.
- This helps form chimeric cages (Protein + inorganic material).
eg. Silver nanocrystals formed inside ferritin cages

↳ Medical applications-

- ferritin can be used as -
MRI contrast agents
diagnostic tools
- Ferritin naturally accumulates in macrophages (immune cells).
- Magnetite (iron oxide) nanoparticles trapped

inside ferritin help in imaging.

- ↳ Scientists engineered ferritin to,
 - make magnetic nanoparticles
 - Add cell-specific targeting peptides on the outer surface

5] Protein-based organelles in bacterial and eukaryotic cells -

- In eukaryotic cells (like plant & animal cells) most metabolic activities happen inside membrane bound organelles such as mitochondria & lysosomes.

- but not all organelles are surrounded by membrane. about 20% of bacteria & eukaryotic cells have protein-based organelles. these organelles are made only of proteins, not membranes.

eg. Natural protein structures are,

- vaults in eukaryotic cells
- Bacterial microcompartments (BMCs) in bacteria.

↳ BMCs -

- BMCs are protein shells that enclose enzymes.

- They are similar in size & shape to viruses.

- there are three main types of BMCs

i. Carboxysomes

ii. Eut BMCs - use ethanolamine

iii. pdu BMCs - use Propanediol.

i) Carboxysomes-

- Found mainly photosynthetic bacteria.
- They are well studied.
- contain two imp enzymes
 - ↳ RuBisCo
 - ↳ carbonic anhydrase
- These enzymes help in CO_2 (carbon) fixation.
- keeping these enzymes inside a protein shell improves carbon fixation.
- Initially, carboxysomes were mistaken for viruses because of their shape.
- They are,
 - polyhedral (many sided)
 - 80-120 nm in size.
 - Made of thousands of protein units
 - The basic building block is a hexamer

↳ Pdu & Eut microcompartments-

- Also polyhedral, but less regular than carboxysomes
- Their metabolic pathways produce aldehydes
- contain more enzymes than carboxysomes.
- Aldehydes are toxic, so these BMCs, protect the cell by keeping harmful compounds inside the compartment

↳ Importance of BMCs

- Their main funⁿ is to reduce exposure of toxic aldehydes in the cell.
- Scientists believe BMCs can be used as,
 - Nano-bioreactors
 - Tools for biosynthesis
 - Biocatalysis
 - Drug & biomolecule delivery system.

- Designed Protein nanoassemblies
- Proteins can act as flexible building blocks for making nanostructures
- In the bottom-up approach, small molecules self-assemble into larger str.
- Proteins are very useful because,
 - i) self assembly
 - ii) easy modification $\rightarrow$ protein funcⁿ can be improved using genetic design, directed evolution.
 - iii) proteins can be chemically modified easily. They are compatible with inorganic materials, so they can be used in new applⁿ beyond traditional biology.

↳ Difficulty in protein folding

- Predicting how a protein folds only from its amino acid sequence is very difficult
- molecular dynamics simulations help understand protein folding, but
- they usually work only for short time periods.
- special supercomputers like Anton are needed.
- most research labs do not have access to such systems.

↳ Alternative approach used by scientists

- because of these limitations, researchers, design protein nanosystems using existing

structural information.

↳ use peptide chains as building blocks
↳ follow a bottom-up approach.

↳ To successfully make nanostructures from natural building blocks, two condⁿ must be met.

i) To correct shape should be present in most of the building blocks.

ii) The fully folded structure must be more stable (lower energy) than unfolded forms (this stability is achieved by favorable interactions betⁿ building blocks).

eg. Cancer drug delivery

- scientists created a chimeric polypeptide containing
 - An ELP (elastin-like polypeptide) segment
 - A cysteine rich region.
- cancer drugs were attached to the cysteine region.
- once drugs were attached, nanoparticles formed automatically.
- These nanoparticles had,
 - A hydrophilic outer layer, A drug-rich core.
- even one treatment was often enough to reduce tumor size.

② Antibacterial nanoparticles -

- Adding hydrophobic cholesterol to hydrophilic peptides encourages nanoparticle formation.

- cell penetrating peptides with arginine residues help self-assembly.
- These peptide nanoparticles, stopped bacterial growth in infected rabbit brains
- Showed antibacterial properties

- ↳ Self assembly in nature vs laboratory
- self assembly is common in nature
 - but it is very difficult to copy perfectly in the lab.
 - nature creates well-ordered structures easily & consistently
 - scientists are still working to achieve the same level of control

- ↳ peptide based nanostructures mainly form through weak (non-covalent) interactions, such as, H-H, Hydrophobic interactions, van der Waals forces.

- ↳ Rgdnor (2007) developed a self-assembling peptide nanoreactor.

- This nanoreactor could produce silver nanoparticles.
- It had multiple internal chambers, like tiny rooms.

- ↳ Padilla & co-workers (2001) created self-assembling nanomaterials such as, protein cages, protein filaments, They

did this by joining naturally symmetrical protein units together.

↳ Haghpanah & colleagues (2009), studied what happens when two diff self-assembling protein domains are combined.

- They found that, The direction of the domains & the no. of domains both affect how well the structure assembles.

2) Matsuda (2012) designed a new C3-symmetrical peptide.

- This design was inspired by virus structure.

- It was used to create spherical peptide nano-assemblies.

Peptide nanotubes.