
SYNTHESIS OF NANOMATERIALS AND THEIR APPLICATIONS

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ABSTRACT:

In the 21st century, nanotechnology has experienced significant growth, thanks to its numerous applications in the field of quantum physics. It has become a highly advanced field of study, with significant efforts focused on researching to apply this technology in practical ways. It shows great potential due to its impressive effectiveness and environmentally friendly characteristics. Nanomaterials are incredibly tiny particles, measuring between 1 and 100 nanometres. Their size grants them unique chemical and physical characteristics, which come with advantages and disadvantages. Their classification can also be done on their composition such as organic, inorganic, and metal. Various techniques are employed to synthesise nanomaterials, including both the "top- down" approach, which starts with bulk materials and breaks them down into nanoparticles, and the "bottom-up" approach, which begins with individual atoms and builds them up into nanoparticles. Among the top-down approaches are "mechanical milling", "nanolithography", ablation", "sputtering", "laser and "thermal evaporation" while the bottom-up approaches are "sol-gel", "biosynthesis", "spinning", "chemical vapour deposition (CVD)", and "pyrolysis". These techniques are highly influenced by factors such as temperature, pressure, time, size and shape, preparation cost, pore size, pH value, and environment. This study examines different methods of synthesizing nanomaterials along with their applications in different fields such as cosmetics, electronics, medicine, food, and the environment.

KEYWORDS: Nanomaterials; Top-down approach; Bottom-up approach; Applications; Nanotechnology; Top-down synthesis; Bottom-up synthesis; Green synthesis; Nanoparticles; Chemical vapor deposition (CVD); Sol–gel method; Hydrothermal synthesis; Characterization

techniques; Biomedical applications; Energy storage; Environmental remediation; Nanoelectronics; Catalysis.

I. INTRODUCTION:

Nanotechnology has garnered significant interest over the course of its development. Nanoparticles serve as the essential building blocks in the field of nanotechnology. They refer to particles with dimensions between 1 nanometre to 100 nanometres, composed of "carbon", "metal", "metal oxides", or "organic substances". They demonstrate distinctive physical, and chemical characteristics when observed at the nanoscale compared to their counterparts at larger dimensions. They can be related to parameters such as greater "surface area to volume ratio", "heightened reactivity or stability", and "improved mechanical strength". The characteristics of nanomaterials have led to their utilization in many applications. Nanomaterials exhibit variations in their components, shapes, as well as sizes, in addition to their material composition. They can exist in various dimensionalities, including "zero-dimensional", "one-dimensional", "two-dimensional", and "three-dimensional" forms. In the "zero-dimensional" case, the nanoparticle is confined to a single axis, as exemplified by nanodots. In the "one-dimensional" case, the nanoparticle possesses only one dimension, as seen in "graphene". "Two-dimensional" nanoparticles have both length as well as breadth, as observed in "carbon nanotubes". Finally, "three dimensional" nanoparticles possess all three parameters, including length, breadth, as well as height, as exemplified by "gold nanoparticles". The nanomaterials exhibit variations in terms of their shape, size, and composition. The particles can exhibit various shapes, such as conical, cylindrical, flat, hollow core, spherical, spiral, tubular, etc., or they may possess irregular shapes. The surface may exhibit either a uniform or uneven topography, characterized by differences in its surface features. Certain nanoparticles are either amorphous or crystalline and are characterized by different crystal solids that can exist in a loosened or consolidated state. with the Various synthesis processes have been adapted to tailor nanoparticles for specific processes, aim of enhancing their chemical, mechanical, optical, and physical characteristics. Significant advancements in technology have resulted in enhanced characterization of nanoparticles and their subsequent utilization. Nanoparticles are being employed in various fields, spanning from cooking vessels and electronics to the solar power and aerospace sectors. Thus, the field of nanotechnology has an important role in fostering a future characterized by environmental cleanliness and sustainability.

II. CLASSIFICATION OF NANOMATERIALS

The nanomaterials can be classified as “organic-based nanomaterials”, “inorganic based nanomaterials”, and “carbon-based nanomaterials”.

1) Organic-Based Nanomaterials:

Dendrimers, ferritin, liposomes, and micelles, among others, are widely recognised as organic-based nanomaterials. The nanoparticles under consideration possess biodegradable properties and are devoid of toxicity. Certain nanoparticles have a hollow core and are commonly known as "nano capsules" and demonstrate sensitivity towards electromagnetic and thermal radiation, including light and heat. The distinctive attributes of these entities provide them with a highly suitable option for the administration of pharmaceuticals. The pharmaceutical's capacity for transporting, its stability, and the delivery method employed, whether it involves adsorbed or entrapped drug systems, are crucial factors that influence their range of applications and overall effectiveness. These factors, in addition to the drug's inherent features such as size, content, and morphology, help in determining the drug's suitability and performance. Organic nanoparticles have gained significant prominence in the biomedical domain, particularly in drug delivery systems, owing to their remarkable efficacy and ability to be administered via targeted administration to specific structural locations.

Definition of Organic-Based Nanomaterials;

Organic nanomaterials consist of polymers, lipids, or small organic molecules structured at the nanometre scale (1–100 nm). Unlike inorganic nanomaterials (like metals or oxides), they are mainly derived from organic chemistry.

Types of Organic Nanomaterials

- **Polymeric Nanoparticles**

Made from natural or synthetic polymers. Used in drug delivery due to controlled release properties.

- **Liposomes**

Spherical vesicles made of lipid bilayers. Common in medical applications for carrying drugs and vaccines.

- **Dendrimers**

Highly branched, tree-like structures with controlled size and shape. Useful in drug delivery and gene therapy.

- **Micelles**

Formed by self-assembly of amphiphilic molecules in water. Used to deliver hydrophobic drugs.

- **Organic Nanofibers**

Fibrous structures with high surface area, used in tissue engineering and filtration.

Key Properties

- Biodegradable and biocompatible
- Flexible and lightweight
- Easy to functionalize (modify chemically)
- Good for targeted delivery in biological systems

Applications

- **Drug Delivery Systems** – Targeted and controlled release of medicines
- **Biomedical Imaging** – Used as contrast agents
- **Tissue Engineering** – Scaffold materials for cell growth
- **Sensors** – Detection of chemicals or biomolecules
- **Environmental Applications** – Water purification and pollutant removal

2) Inorganic Based Nanomaterials:

Inorganic nanomaterials are defined as “particles composed of elements other than carbon”. They are often classified as “metal-based nanomaterials” and “metal oxide-based nanomaterials”.

- **Metal-based nanomaterials:**

Metal-based nanomaterials are a type of nanomaterials that are produced by reducing or constructing metals into nanometric dimensions. The metals usually used in the manufacture of nanomaterials include silver (Ag), aluminium (Al), gold (Au), cobalt (Co), cadmium (Cd), copper (Cu), lead (Pb), iron (Fe), and zinc (Zn). Nanomaterials possess unique attributes, including dimensions between 10nm to 100nm, and surface properties characterised by a "high surface area to volume ratio", "pore size", "surface charge", and "surface charge density". Additionally, they exhibit amorphous as well as crystalline structural properties, and come in various shapes such as cylindrical or spherical and display distinct colouration. Furthermore, nanoparticles demonstrate reactions and adaptability to environmental factors like air, sunlight, heat, and moisture.

- **Metal oxide-based nanomaterials:**

The synthesis of metal oxide nanomaterials is done to alter the properties of their corresponding metal nanomaterials. For instance, iron (Fe) nanomaterials undergo immediate oxidation to form iron oxide (Fe_2O_3) when exposed to oxygen at ambient temperature. This transformation enhances the reactivity of the nanoparticles as compared to pure iron nanomaterials. Metal oxide nanomaterials are primarily synthesized because of their enhanced reactivity as well as efficiency. The following compounds are frequently synthesised: Aluminium oxide (Al_2O_3), Zinc oxide (ZnO), Silicon dioxide (SiO_2), Cerium oxide (CeO_2), Iron oxide (Fe_2O_3), Magnetite (Fe_3O_4) and Titanium oxide (TiO_2). These nanomaterials exhibit extraordinary features in comparison to their metallic counterparts.

3. Carbon-Based Nanomaterials:

Nanomaterials composed entirely of carbon are commonly referred to as carbon-based nanomaterials. The entities can be categorised as “carbon black”, “carbon nanofibers”, “carbon nanotubes (CNT)”, “fullerenes”, and “graphene”.

- **Carbon black:**

Carbon black, being an amorphous material, exhibits a lack of a definite crystalline structure. It is typically found in a spherical form, with dimensions ranging from 20 to 70 nm. The level of nanomaterial contact is sufficiently intense to result in their aggregation, leading to the formation of agglomerates measuring around 500 nm in size.

- **Carbon nanofibers:**

The utilisation of graphene nano foils to produce carbon nanofibers involves the formation of conical or cup-shaped structures, as opposed to the conventional cylindrical tubes employed in carbon nanotubes (CNTs).

- **Carbon nanotubes (CNT):**

Carbon nanotubes (CNTs) are of cylindrical shape with a composition of graphene, a 2D nanomaterial with a honeycomb-like lattice of carbon atoms. They can be as small as 0.7 nanometres for one-layered and 100 nanometres for multi-layered CNTs. Additionally, their diameters can range from some micrometres up to several millimetres. The terminations of the structure have the potential to exhibit either a hollow configuration or a closure facilitated by half fullerene molecules.

- **Fullerenes:**

Fullerenes, namely the C₆₀ molecule, exhibit a spherical morphology and consist of carbon atoms interconnected through sp² hybridization. The formation of spherical structures with sizes of single-layer being 8.2 nm and 4-36 nm for multiple layered fullerenes is observed.

- **Graphene:**

Graphene can be classified as an allotrope of carbon. It is a 2D flat surface having a hexagonal network of carbon atoms arranged in a honeycomb lattice structure. Typically, the dimension of a sheet of graphene is approximately 1 nm.

III. SYNTHESIS OF NANOMATERIALS;

Two prominent approaches used for the synthesis of nanomaterials are "top down" and "bottom- up".

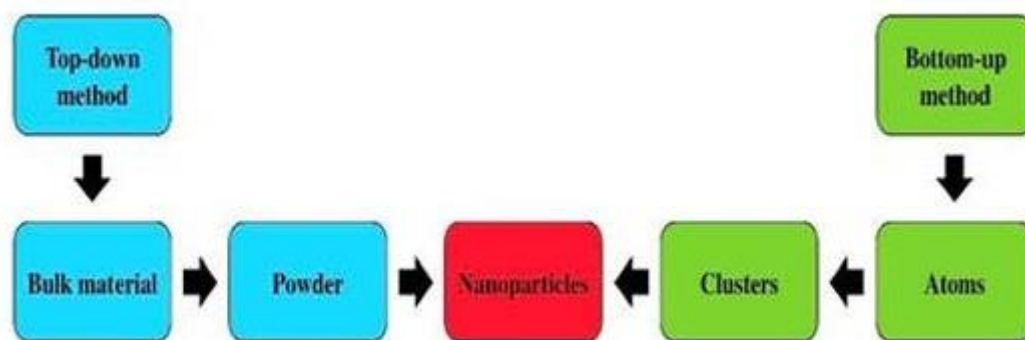


Figure 1: Synthesis of nanomaterials.

The top-down approach refers to the involvement of the mechanical fabrication of bulk materials, leading to the development of small particles with nano-scale dimensions. In bottom-up methods, nanomaterials are formed by means of self-assembly or co-precipitation techniques, wherein the tiny particles are brought together and organised.

These techniques are further divided into the following classes:

- **Physical Methods:**

There are two types of physical methods for synthesizing nanoparticles, namely, “mechanical type” and “vapour deposition type”. They work at the highest temperature which is greater than 350 degrees Celsius.

- **Chemical Methods:**

The chemical methods that help in the synthesis of nanomaterials usually work at

temperatures less than 350 degrees Celsius. Though they are inexpensive and small methods, due to the **different shapes and sizes of nanomaterials, large quantities can be generated.**

- **Biological Methods:**

These methods, also called “green synthesis”, are based on the usage of microorganisms, plant extracts, or templates that may include membranes, viruses, DNA, etc. They are non-toxic and eco-friendly methods for synthesizing nanomaterials.

1) . Factors Affecting Synthesis of Nanoparticles:

- **Temperature:**

Temperature is one of the most important factors that affect methods of synthesis of nanoparticles. For instance, physical methods work at temperatures above 350 degrees Celsius while chemical methods operate below 350 degrees Celsius. Further, biological methods require temperatures less than 100 degrees Celsius.

- **Pressure:**

Since the amount of pressure applied to nanomaterial affects its shape and size, it is the second most important parameter that affects the synthesis of nanoparticles.

- **Time:**

The time duration during which the reaction takes place affects the type and quality of nanoparticles being synthesized.

- **Size and Shape:**

The synthesis of nanoparticles is affected by the particle size, colour of light being emitted, and shape of nanoparticles.

- **Preparation Cost:**

The preparation cost of synthesis is one of the issues that determine the application of the nanomaterials. For instance, physical methods are relatively costly than chemical methods. Further, biological methods are cheaper than both methods due to which biological methods find their application in large-scale synthesis of nanoparticles.

- **Pore Size:**

The porosity characteristic of nanoparticles affects the quality of nanoparticles being synthesized. This parameter holds great importance when it comes to dealing with drug delivery systems.

- **pH Value:**

Understanding pH value is important when it comes to adopting chemical or biological

synthesis methods. Also, the pH value affects the texture as well as the size of the synthesized nanomaterials.

- **Environment:**

The environment is one of the factors affecting the synthesis of nanomaterials, specifically while adopting biological methods. It further affects the physical as well as chemical properties of the produced nanoparticles.

Table 1. Categories of the nanoparticles synthesised from the various methods

Category	Method	Nanoparticles
Bottom-up	Sol-gel	Carbon, metal and metal oxide based
	Spinning	Organic polymers
	Chemical Vapour Deposition (CVD)	Carbon and metal based
	Pyrolysis	Carbon and metal oxide based
	Biosynthesis	Organic polymers and metal based
Top-down	Mechanical milling	Metal, oxide and polymer based
	Nanolithography	Metal based
	Laser ablation	Carbon based and metal oxide based
	Sputtering	Metal based
	Thermal decomposition	Carbon and metal oxide based

2. Top-down approaches:

With this technique, it's possible to decrease large amounts of material to generate particles at the

nanoscale. The top-down approaches use nanoparticles with macroscopic initial structures and work on the grinding process. While top-down methods can be executed in a simple manner, they are not effective to produce irregular shaped or very small particles due to their imprecision. Its major drawback is the difficulty in achieving the desired size and form. Among the top-down approaches are “mechanical milling”, “nanolithography”, “laser ablation”, “sputtering”, “evaporation” and “thermal evaporation”.

3. Bottom-up approaches:

The bottom-up approach involves NMs self-assembling from smaller atoms and molecules to form a certain size, shape, and chemical content. This approach works on the principle of “molecular recognition” and involves “atom-by-atom”, “molecule-by-molecule”, or “cluster-by-cluster” manipulation. Among the bottom-up approaches are “sol-gel”, “biosynthesis”, “spinning”, “chemical vapour deposition (CVD)”, and “pyrolysis”.

- **Mechanical milling:**

Mechanical milling is widely employed as the predominant top-down approach for the synthesis of diverse nanoparticles. It is a commonly employed technique for the milling and subsequent annealing of nanomaterials in the process of synthesis. This method involves the milling of various materials inside an environment that is devoid of reactive gases or substances. Plastic deformation is an important aspect in mechanical milling since it contributes to the alteration of

particle morphology. Fracture, on the other hand, results in a reduction in the size of particles, while cold welding results in an increase in the size of the particles.

- **Nanolithography:**

Nanolithography refers to the scientific investigation of the production of structures at the nanoscale, whereby at least one-dimension falls within the range of 1nm to 100 nm. There exist multiple nanolithography methods, including electron-beam, multiphoton, optical, nanoimprint, and

scanning probe lithography. Lithography is a widely employed technique in which a desired form or structure is printed onto a light-sensitive substance, resulting in a particular elimination of material to

achieve the intended shape or structure. One of the primary benefits of nanolithography is its ability to generate structures ranging from individual nanoparticles to clusters of predetermined shape and size.

One of the drawbacks of this approach is the necessity for advanced technology and the accompanying financial implications.

- **Laser ablation:**

The laser ablation technique is widely employed for the synthesis of nanomaterials using different solvent systems. The utilisation of a laser beam to irradiate a metal that is immersed in a liquid medium leads to the condensation of a plasma plume, resulting in the generation of nanomaterials. The top-down approach discussed herein offers a dependable method that presents an alternative answer to the traditional chemical reduction process for synthesising metal-based nanomaterials. The utilisation of laser ablation for the synthesis of nanomaterials in both water and organic solvents, without the need for stabilising chemicals or agents, renders it an environmentally friendly approach.

- **Sputtering:**

Sputtering refers to the process of depositing nanomaterials onto a surface through the

ejection of elements from such surfaces as a result of collisions with ions. The process of sputtering

typically involves the deposition of a thin coating of nanomaterials, which is subsequently followed by annealing. The dimensions and morphology of the nanomaterials are influenced by factors like surface temperature, thickness, and length of the annealing process, and the kind of substrate.

- **Thermal decomposition:**

Thermal decomposition refers to a chemical process of break down that occurs because of the input of heat energy, leading to the breaking of chemical bonds within the material. The decomposition temperatures refer to the temperatures when a nanomaterial undergoes chemical decomposition. The development of nanomaterials includes the decomposition of metal at a certain temperature, resulting in a chemical reaction that yields secondary compounds.

- **Sol-gel:**

The sol-gel process is widely favoured as a bottom-up approach due to its inherent simplicity and the fact that most nanomaterials can be synthesised using this technique. The wet-chemical method involves the utilisation of a chemical solution that serves as an early stage for a cohesive system comprised of distinct particles. Metal oxides as well as chlorides are commonly employed as the beginnings of the sol-gel method. The starting point is subsequently disseminated throughout a host liquid using methods such as shaking, sonication, or stirring resulting in a system including both the solid and liquid phases. Various processes, including centrifugation, filtration, and sedimentation are employed in a phase separation process that retrieves nanomaterials. Additionally, the moisture content is subsequently reduced through the process of drying.

- **Biosynthesis:**

Biosynthesis represents an ecologically sustainable method to produce nanomaterials that possess characteristics of being non-toxic and capable of undergoing biodegradation. It employs biological sources such as bacteria, fungi, plant extracts, and similar organisms, in conjunction with basic materials, to generate nanomaterials as an alternative to conventional chemical methods, namely for the applications of bio reduction and capping. The nanomaterials that are synthesised by biosynthesis exhibit distinct and improved characteristics, making them suitable for many biomedical applications.

- **Spinning:**

The process of synthesising nanomaterials through spinning is conducted using a spinning disc reactor (SDR). The apparatus consists of a chamber or reactor housing a revolving disc, which allows for precise control of physical factors such as temperature. To mitigate the impact of chemicals, the reactor is typically purged with inert gases such as nitrogen in order to eliminate oxygen. The disc undergoes rotation at varying velocities, while the liquid, specifically the precursor and water, is introduced through pumping. The rotational motion induces the fusion of particles or atoms, resulting in precipitation, subsequent collection, and subsequent drying (Mohammadi et al., 2014). The features of nanomaterials synthesised through SDR are determined by several operating factors, including the disc surface, disc spinning speed, feed location, liquid flow velocity, liquid/precursor ratio, and others.

- **Chemical Vapour Deposition (CVD):**

Chemical vapour deposition (CVD) is the process by which gaseous reacting agents are combined to form a thin film as the coating over the surface. The deposition process is conducted within a reaction chamber operating at room temperature, wherein the molecules of gases are combined. A reaction is initiated when a substrate is subjected to heat and subsequently interacts with a mixture of gases. The chemical reaction yields a slender layer of the desired product on the substrate's surface, which is subsequently collected and employed. Its temperature greatly influences the CVD process. The process has several notable advantages, including the production of nanomaterials that exhibit exceptional levels of purity, uniformity, hardness, and strength. One of the drawbacks associated with CVD is the necessity for specialised equipment, while another concern is the highly toxic nature of the gases that are produced as by-products.

- **Pyrolysis:**

Pyrolysis is the prevailing method employed in industrial settings for the purpose of achieving substantial quantities of nanoparticles. The process entails the combustion of a precursor using an open flame. The precursor, in either liquids or gaseous form, is introduced inside the furnace at elevated pressure via a narrow aperture, where it undergoes combustion. The gases resulting from combustion or by products are subsequently subjected to air classification to retrieve the nanomaterials. Certain furnaces employ laser and plasma technology as an alternative to traditional combustion methods to generate elevated temperatures conducive to efficient evaporation. Pyrolysis offers several advantages, including its simplicity, efficiency, cost-

effectiveness, and ability to operate continuously while achieving high yields.

IV. APPLICATIONS OF NANOMATERIALS;

1. Cosmetics:

The typical sunscreen creams designed to provide protection against UV radiation exhibit limited durability over extended periods of use. The utilisation of zinc oxide (ZnO) and titanium oxide (TiO₂) nanomaterials in certain sunscreens has been attributed to their UV protection capabilities, which arise from their transparency to visible light along with their ability to absorb as well as reflect UV radiation.

2. Electronics:

The increasing need for larger and brighter displays in television and computer monitors has led to a growing interest in utilising nanomaterials in display technologies. Nanocrystalline cadmium sulphide, lead telluride, and zinc selenide have been employed in the LEDs found in contemporary displays. The proliferation of portable consumer devices, including mobiles and laptops, has resulted in a significant increase in the need for batteries that are lightweight, compact, and possess high capacity. Nanomaterials represent a highly favourable option for the implementation of separator plates inside battery systems. The aerogel structure of these batteries enables a significantly higher energy storage capacity in comparison to conventional batteries. Batteries composed of nanomaterials exhibit enhanced performance characteristics, such as reduced recharging requirements and extended lifespan, owing to their substantial surface area. The utilisation of nanoparticles enhanced electrical conductivity has been employed for the detection of gases such as NH₃ and NO₂. The observed phenomenon can be attributed to the augmentation of nanomaterial's porosity resulting from the transfer of charge from nanomaterials to NO₂, which facilitates the binding of gas particles and enhances their efficacy as gas sensors.

3. Medicine:

The application of nanomaterials in the administration of medicines has significantly enhanced the healthcare sector. Nanomaterials have been demonstrated as a viable means of targeted drug delivery to specific cells. The administration of drugs at the appropriate site and dosage leads to a substantial reduction in overall drug consumption and associated adverse effects. This approach effectively mitigates both the financial burden and adverse effects. Nanotechnology can facilitate the process of tissue engineering, which involves the replication and restoration of damaged tissue. Tissue engineering has the potential to supplant conventional therapeutic approaches, such as organ transplants and artificial implants. An

illustrative instance pertains to the proliferation of bone CNT scaffolds. The utilisation of gold in the field of medicine has a longstanding history. An often-prescribed intervention is the utilisation of gold as a means to increase memory function. In order to improve the cognitive well-being of an infant, gold is incorporated into specific pharmaceutical formulations.

4. Food:

The integration of nanotechnology facilitates advancements in the domains of food manufacturing, processing, safety, and marketing. An instance of the utilisation of nanocomposite coatings in the food packaging business involves the direct incorporation of antimicrobial compounds onto the surface of the coated film. An illustration may be seen in the canola oil manufacturing sector, whereby nano drops are employed as an additive with the purpose of facilitating the transfer of vital minerals and vitamins present in the food.

5. Environment:

Nanomaterials possess distinctive physical and chemical characteristics that render them highly suitable for utilisation in contemporary environmental remediation practises, as well as for augmenting the efficacy of renewable energy systems. They have been effectively employed for more than ten years in the field of environmental remediation, specifically in the treatment and decontamination of air, water, and soil. Nano remediation is considered an efficacious approach because of its ability to provide in situ treatment, hence obviating the requirement for groundwater extraction and construction to access the intended site. Nanomaterials are employed for the purpose of surface water treatment, encompassing disinfection, purification, and desalination. They are utilised for the purpose of oil spill remediation, and their efficacy in this application has been widely known. They are primarily employed for the purpose of treating wastewater, in addition to the sludge generated in these processes. The remediation of contaminated soil involves the utilisation of tiny particles, which are introduced into predetermined sites to address issues such as heavy metal contamination and hazardous industrial waste. The inherent hydrophobic characteristic exhibited by some nanomaterials has facilitated the development of self-cleaning solar power cells.

CONCLUSION

Nanomaterials have revolutionized multiple fields due to their unique properties. Advances in synthesis techniques have enabled precise control over their structure and functionality. With continued research and development, nanomaterials are expected to play a crucial role in

solving global challenges in healthcare, energy, and the environment.

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