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Nanostructures for Virus Detection and Tracking: An Overview

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Abstract

Treatment of viral diseases and subsequent patient recovery depends on the timely identification of analytes such as viral proteins, nucleic acids and antibodies that are produced as part of the body's immune response to infection. Current diagnostic procedures require specialized and expensive personnel and are performed in special testing centers, leading to lengthy processes and delays in effective treatment. Due to the unique properties of Nanostructures that can be used to detect analytes in very small amounts, much research has been conducted on the use of nanostructures to detect and track viruses. In this article, we divide the nanostructures proposed in this field into 3 groups of carbon, inorganic and organic Nanostructures, and separately study their efficiency in the 2 fields of virus detection and tracking.

Keywords: Nanostructure, Organic, Inorganic, Carbon, Tracking viruses

Abbreviations

Molecularly imprinted polymer nanoparticles	(MIP-NPs)
Magnetic nanoparticles	(MNPs)
Radiotherapy	(RT)
Superparamagnetic press oxide nanoparticles	(SPIONs)
Mesoporous silica nanoparticles	(MSNs)

Introduction

Viruses are infectious microorganisms that replicate inside the host cell. Viral particles are unable to replicate like most other forms of life. In response to viral infection, the host cell must quickly replicate the invading virus in an enormous number of copies [1-4]. The infected host cell becomes a breeding ground for new viruses, which may change and develop thanks to their genes, unlike simpler infectious agents. The number of known viral types exceeds 5,000 [5-7]. Viruses have no known genesis. Some are bacterial in origin, while others developed from plasmids (DNA fragments capable of transferring between cells). Viruses are always composed of 2 or 3 pieces. A lengthy molecule that holds genetic information is the first component, the gene. Genes may be composed of either DNA or RNA [8-11]. The second component is a gene-protecting protein layer. Encouraging some viruses to enter host cells, a lipid coating encases their protein coat and binds to certain receptors. Viruses may take many forms, from basic icosahedrons and spirals to more intricate geometries. There are 33,000 to 500,000 viruses per centimeter, given that viruses range in size from 20 to 300 nm [12-16]. There are a lot of ways that viruses may propagate. There are a lot of viruses that can only infect certain kinds of hosts or types of tissues. The replication process is essential for all viruses [17,18]. Vectors, which may include insects, are responsible for transmitting viruses from 1 plant to another. Viruses in animals, including humans, may transfer from 1 host to another by direct contact with infected blood, saliva, or other body fluids. When people cough or sneeze, they release moisture droplets into the air, which may carry

viruses like the influenza virus [19-22]. The fecal-oral cycle is a vector for the transmission of viruses like norovirus via contaminated hands, food, and water. The most common way to get rotavirus is to touch a sick youngster. One of the ways that human immunodeficiency virus (HIV) may be spread is via sexual contact and other body fluids. Bloodsucking insects are the vector for the transmission of some viruses, such the dengue virus. Diseases may be caused by viruses in plants, animals, and people alike [23-27]. Nonetheless, the immune system of the host organism often eliminates them, and the host develops a permanent resistance to them. Viruses are immune to antibiotics, however there are antiviral medications that may cure serious viral infections. Some viral infections may be prevented using vaccines that provide long-term or permanent protection [28-31]. Today, the Chamberland filter - also called the Chamberland-Pasteur filter - was designed by French microbiologist Charles Chamberland in 1884. Because the holes of this filter are smaller than those of bacteria, he was able to successfully strain a bacterial solution by passing it through it [32-35]. Russian scientist Dmitri Ivanovsky used this filter in the early 1890s to study the Tobacco mosaic virus, which gained widespread recognition at the time. Extracts from crushed diseased tobacco leaves maintained their infectiousness after filtering, according to his research [36-40]. Simultaneously, more than a handful of researchers demonstrated that these agents, which would subsequently be known as viruses, could nonetheless infect humans despite their size being almost a tenth that of bacteria. This factor replicates only in cells that are dividing, as noted by the Dutch scientist Martinus Beijerinck in 1899 [41-44]. He dubbed it “soluble living matter” as he was unable to determine the composition of the agent’s particles. At the turn of the twentieth century, 2 bacteriologists - Frederick Tourette of England and Felix Drell of France and Canada - described viruses that infected bacteria and destroyed bacteria cultured on agar. He was able to determine the viral load in the suspension by counting the places where bacteria had been destroyed [45-50]. The first pictures of viruses were captured in 1931 when German engineers Ernst Ruska and Max Knoll invented the electron microscope. The majority of the tobacco mosaic virus was shown to be protein in 1935 by American scientist and virologist Wendell Meredith Stanley [51-53]. The arane and protein components of this virus were isolated shortly thereafter. Researchers back then had no idea how to culture viruses in a controlled environment; this was a major obstacle to their work. In 1931, the issue was resolved when Ernest William Goodpasture and Alice Miles Woodruff, 2 American pathologists, succeeded in cultivating influenza and other viruses in fertilized eggs [54-58]. In 1949, researchers John Franklin Enders, Thomas Huckle Weller, and Frederick Chapman Robbins successfully cultivated Human enterovirus C in live animal cell cultures, overcoming the challenge of growing some viruses in eggs. More than 5,000 different viral kinds have been identified so far using these approaches. Virion, another name for a virus particle, is a protective protein coating that encases DNA or RNA genes. The many tiny, identical protein molecules that make up this capsid are known as capsomers [59-62]. Capsomers may have a variety of arrangements, including icosahedron, helical, and more intricate ones. The nucleocapsid is a protein-containing outer shell that encases DNA or RNA. An envelope of lipid surrounds certain viruses. Viruses are so tiny that they are only visible under an electron microscope; a light microscope is unable to reveal them. In terms of size, they range from 20 to 300 nm [63-66]. A centimeter (0.39 inches) in length contains anything from 33,000 to 500,000 viruses due to their minuscule size. Cells of more complex creatures may measure tens of micrometers, whereas bacteria usually measure about 1 μm (1,000 nm). Mega viruses and Pandora viruses are 2 examples of viruses that are quite huge, measuring around 1 μm [67-70]. The discovery of these 2 amoebas-infecting viruses occurred in 2003 and 2013, correspondingly. Scientists were taken aback by the finding of these “giant” viruses, which are about a thousand times bigger than influenza viruses. The DNA or RNA of an organism contains all of its biological information. Although DNA is the most common genetic material, RNA is the primary genetic material for many viruses [71-73]. A virus’s genetic material, known as DNA or RNA, may be either single-stranded or double-helical. Since viruses only contain a few of genes as opposed to the 20,000 - 25,000 genes found in humans, they can replicate rapidly. Rotavirus, in contrast to influenza virus, contains eleven genes. Some of these gene’s code for structural proteins that are ubiquitous across viruses, whereas others code for non-

structural proteins that are exclusive to cells infected with the virus [74-77]. Genome replication is facilitated by enzyme proteins known as DNA polymerase and RNA polymerase, which are present in all organisms and a large number of viruses. When compared to enzymes found in host cells, viral polymerase enzymes typically produce DNA and RNA with a much higher efficiency. One reason arane viruses often evolve to create new strains is because arane polymerase enzymes are prone to making errors. Some arane-containing viral species carry their genes on distinct molecules rather than a single continuous one [78-82]. As an example, the influenza virus has 8 distinct Arane genes. During recombination, which occurs when 2 influenza virus strains enter a cell, the virus's genes may mingle to create new strains. All living things need proteins. Cells synthesize new protein molecules from the building blocks of amino acids according to the instructions written in DNA. Since most proteins are highly specialized and can only carry out a single task, cells will need to synthesize new proteins if they acquire new cellular requirements [83-85]. To ensure the virus's continued viability, viruses coerce cells into producing proteins that are superfluous to the cell's function. There are primarily 2 phases to the protein-making process [86-90].

To make copies of RNAs called messenger RNA, the genetic code included in DNA must be used in a process known as transcription. Protein synthesis begins with the transmission of genetic instructions to the ribosome, which occurs when these chemicals move through the cell. Because the messenger codons dictate the protein's amino acid structure during translation, this process is known as translation. Amino acid language is therefore established by translating information from nucleic acid language.

Some arantevirus nucleic acids provide the same function as messenger RNAs. The term "Aran virus with positive polarity" describes these viruses precisely because of this. The arane strand is the complementary strand of messenger RNA in other viruses that include arane, and these viruses either employ cell enzymes or produce their own messenger RNA. Arane viruses with negative polarity are the name given to these viruses [91-94]. The process of mRNA synthesis in DNA viruses is comparable to that in cells. Retroviruses operate in a totally different way; while they possess RNAs, they employ reverse transcriptase inside the host cell to create a DNA copy of their RNAs. After then, the DNA is integrated into the host's DNA and duplicated in the messenger RNA via the cell's regular routes [95-97]. Viruses may alter host cell structure and biochemistry in many different ways. Cytopathic effects describe these side effects. The host cell dies as a final outcome of the majority of viral infections. There are a number of ways in which cells might die, including apoptosis, alterations to their surface membrane, and cell rupture. Even if proteins aren't the only part of a virus, they may impair normal functions, which can lead to cell death. When infecting cells, certain viruses do not alter their appearance in any noticeable way [98-102]. There are often no symptoms of infection and the cell continues to operate properly while the virus is dormant and inactive. Consequently, the infection lingers and the virus often goes dormant for a long period of time. The Herpesviridae family of viruses often causes this kind of illness. While the human papillomavirus is a leading cause of cancer, other viruses, such the Epstein-Barr virus, stimulate cell proliferation without creating malignant tumors [103-105]. When a virus damages a cell's DNA and the cell is unable to fix it, apoptosis occurs. The cell's own degradation of the damaged DNA is an outcome of cell death. To ensure that host cells do not perish before they can replicate, certain viruses incorporate mechanisms to restrict cell death. Consider the HIV epidemic as an example [106-110]. Among humans, the most prevalent viral illnesses are herpes simplex, chickenpox, influenza, and the common cold. Ebola and acquired immune deficiency syndrome are 2 severe illnesses that may be caused by viruses. Numerous viruses are deemed "benign" because they are either not pathogenic or only cause minor sickness. Pathogenic viruses are the most dangerous kind of virus [111-114]. Many different illnesses may be caused by viruses, which vary in the kind of cells they infect. In chronic infections, the virus keeps multiplying in the host's body even after the host takes all necessary precautions to stop it. This kind of infection may last a person's whole life. When it comes to hepatitis and hepatitis C, this happens rather often. Vectors are defined as individuals who acquire persistent viral infections. They play a crucial role in keeping the virus alive [115-120]. A disorder is considered endemic if it affects a significant portion of a certain community.

Despite the multiplicity of viral vectors, most viruses only use a few of them while transferring from one host to another. Vectors spread several plant-infecting viruses. Vectors, which are often insects that feed on blood, are responsible for the transmission of several viruses that infect animals, including humans. Nevertheless, this population is more prone to virus transmission by direct contact. Airborne viruses are one kind of viral illness; others, like rotavirus and norovirus, may be transmitted by contaminated food or drink, hands, or household objects; and still others can be acquired through intimate contact with other affected individuals [121-124]. Intercourse between unprotected sexual partners or intravenous injections may spread viruses including HIV, hepatitis B, and hepatitis C. Understanding the mechanisms of viral transmission is crucial for the prevention of infections and outbreaks. Vaccination is a method forwarding against viral infections. Vaccines do not really cause illness, but rather imitate the immune system's response to a genuine infection [125-130]. Vaccines have greatly decreased the morbidity and death caused by infectious illnesses including rubella, polio, measles, and Oregon, and they have even eliminated chickenpox. More than 14 viral illnesses in humans have vaccines, and several more are in the works for animals. Vaccines may include both live and dead viruses. A weakened virus is included in live vaccinations. But these immunizations pose a risk to immunocompromised individuals as the disease-causing virus might still be present in a weaker form. "Recombinant" vaccinations, made possible via genetic engineering and biotechnology, contain just the viral capsid protein. This class of vaccines includes, for instance, the Hepatitis B vaccination [131-135]. The lack of pathogenicity in these vaccinations makes them more secure. The fast development of antiviral medications has been driven by the AIDS pandemic, which began in the mid-1980s. Many antiviral medications belong to a class of medications called nucleoside analogs. While their molecular structure differs from that of DNA, they share the same family of molecules. Some of these synthetic components end up in the viral genome when replication of DNA starts [136-141]. The virus is unable to replicate beyond this point due to a halt in gene replication and the fact that the synthetic building blocks do not possess the necessary qualities for the addition of more blocks. Among the many examples of nucleoside analogs are the anti-herpes drugs acyclovir and the anti-AIDS and hepatitis B drugs lamivudine. Acyclovir is a popular and long-standing antiviral medication. A variety of other antiviral medications target distinct phases of the viral life cycle. The infectious properties of HIV are dependent on an enzyme known as HIV protease [142-148]. Protease inhibitors are a family of medications that may bind to this enzyme and prevent it from doing its job. An arane virus causes hepatitis C. Unless treated, 80 % of infected persons will live with chronic illness. Ribavirin, a nucleoside analog, and Interferon form an effective treatment regimen. The same approach has been used to treat chronic hepatitis B virus carriers with lamivudine and other antiviral medications [149,150]. Medication inhibits viral replication in both conditions, while interferon eliminates any residual infected cells. Treatment for HIV infection often involves a cocktail of antiviral medications, each of which inhibits a distinct phase of the virus's life cycle. Several of the currently available medications work by blocking the virus's ability to bind to cells, while others deactivate the enzymes required for viral replication, and still others are nucleoside analogs. The significance of understanding viral replication is shown by the effectiveness of these medications [151-155]. Underwater habitats are teeming with viruses. A teaspoon of saltwater contains around 1,000,0000 viruses. Both freshwater and saltwater ecosystems rely on viruses for regulation. Bacteriophages, the most common kind of virus, pose no threat to living things. Their ability to infect and kill bacteria in aquatic microbial communities is the single most essential thing that marine ecosystems do to recycle carbon. The viral release of organic compounds from bacterial cells promotes the proliferation of both bacteria and algae. Over 90 % of marine biomass consists of microorganisms [156-160]. Viruses kill off around 20 % of this biomass daily, and there are fifteen times as many viruses as bacteria and archaea in the water. Invasive algal blooms may quickly wipe out whole ecosystems, and viruses are mostly to blame for this. As 1 descends further into the ocean, one finds a smaller concentration of viruses. Because the number of hosts is lower there [161-164]. There is a wide range of things that viruses can do. There is an indirect effect of viruses on atmospheric carbon dioxide levels of around 3 Gtons per

year because to the increased respiration in the seas. Viruses may infect both land and sea creatures [165-167]. The jaw distemper virus was responsible for the deaths of thousands of Phocavitulina throughout Europe between 1988 and 2002. Various different types of viruses are present in populations of marine mammals. These include calicivirus, Herpesviridae, Adenoviridae, and parvovirinae [168-172].

The impact of the coronavirus outbreak on global health and healthcare systems has demonstrated, more than ever, the importance of timely and cost-effective viral diagnostics [173-175]. The need for a highly sensitive system with easy operation, caution, and the development of suitable methods, such as ELISA (enzyme-linked immunosorbent assay), PCR (polymerase chain reaction), serological antibody determination, Western blot assay, etc. desire to replace common diagnostic methods [176,177]. Current methods not only require sophisticated laboratory equipment and the presence of skilled personnel to operate the equipment, but also increase the cost of testing [178-180]. One of the main features of the alternative method is its rapid response and no need for special equipment, which has always been the focus of researchers in this field. On the other hand, the low stability and low luminescence intensity of fluorescent markers are the main obstacles in understanding the mechanism of viral infection, delaying the development of antiviral drugs [181,182]. Viruses have been responsible for several large epidemic outbreaks with high mortality rates throughout human history. While the lethality of viruses is well known, **Figure 1** shows the damage caused by the spread of various viruses. The order of types ranges from those causing the most deaths to those causing the fewest casualties. Nanostructures are suitable additives to improve the resolution and signal response of diagnostic and imaging systems due to their exceptional surface-to-volume ratio, quantum confinement, and charge transport properties [183-186]. In the field of virus detection, Nanostructures have a significant advantage over organic dyes due to their properties [187-190]. Next, we will look at the nanostructures used to detect and track viruses. Infectious diseases come in a variety of sizes and shapes (**Figure 2**), but are made up of 2 key components: A genetic core (RNA or DNA) and a protein outer shell, the capsid. Virions come in 4 different morphologies: H. circular, helical, polyhedral, and complex. Coronaviruses have positive-stranded RNA (+ssRNA) with a crown-like structure and spike glycoproteins on their envelope [12].

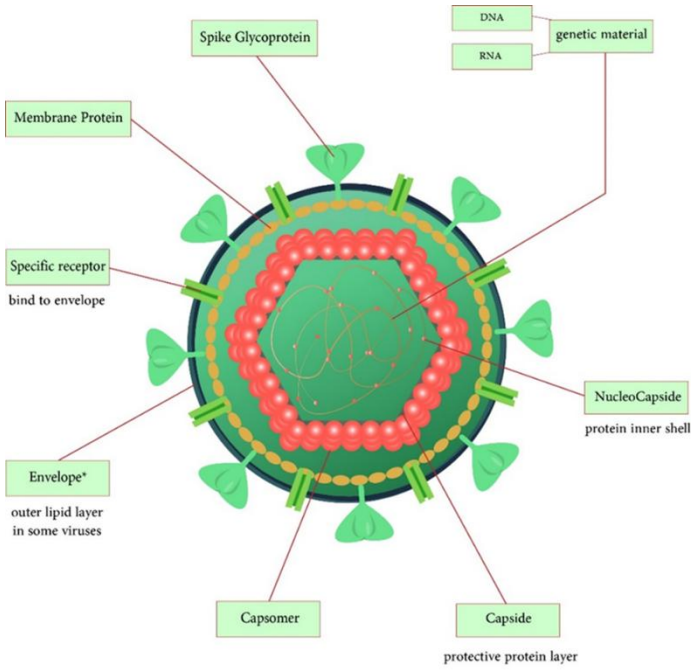

Figure 1 Viruses that have caused large-scale infectious diseases in human history, arranged in descending order of casualties [17-22].

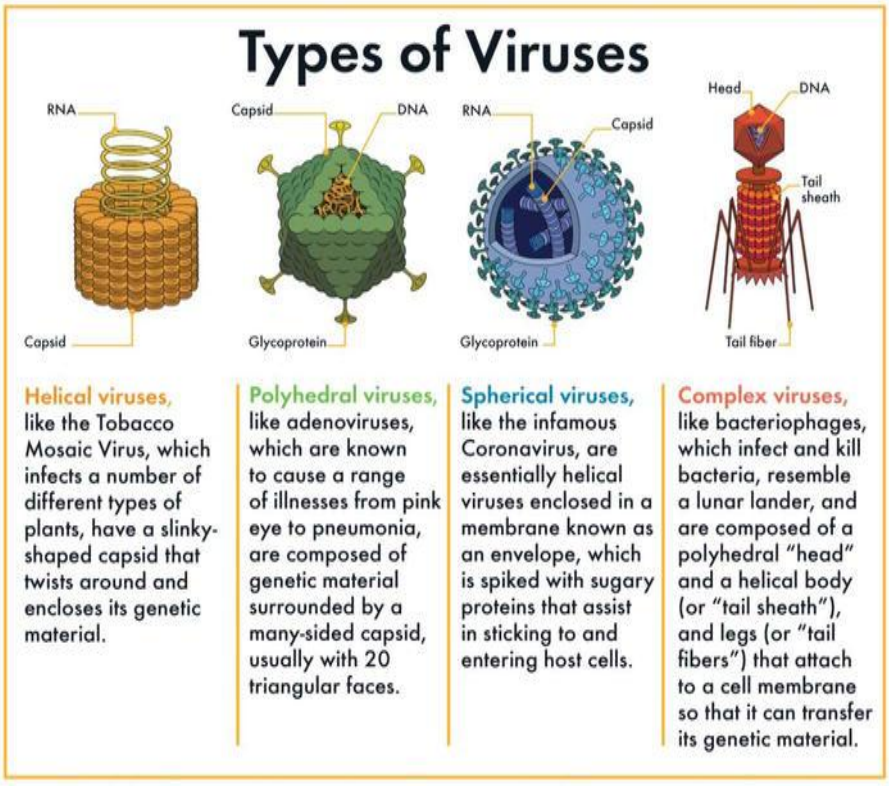

Figure 2 Types of viruses [48].

Nanostructures based on carbon allotropes in the detection and tracking of viruses

Carbon is found abundantly on earth and therefore it is used in many different fields of science and technology [23-25]. Elemental carbon exists in the form of different allotropes based on the hybridization of its atoms, and several different forms of this material are known at the nano scale, such as carbon dots, graphene quantum dots, fullerene, carbon nanotubes, and graphene (**Figure 3**) [26,27].

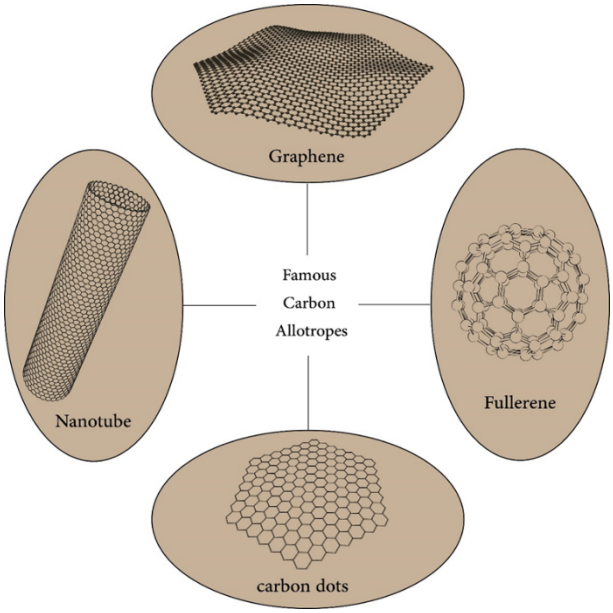

Figure 3 Nanostructures based on carbon allotropes in the detection and tracking of viruses [27].

Detection of viruses

Nanotechnology enhances examination methods and imaging diagnostics, paving the way for earlier diagnoses of incurable diseases like cancer and improved patient treatment. While many nanomedicines have been developed, most remain in the research and patent stages [191-193]. Some have passed these stages and, after receiving the necessary approvals, are now in production and clinical use. A report from the US Food and Drug Administration (FDA) reviewed approximately 350 nanomedicines approved by the organization up to 2016, indicating that these therapies are most commonly used for cancer, inflammation, pain, and infections [194-197]. However, the use of nanomedicine for common diseases such as diabetes, hypertension, and cardiovascular conditions has not yet been reported. Regarding nanocarriers, liposomes, nanocrystals, emulsions, polymeric compounds, and micelles are the most frequently employed. In contrast, nanostructures like carbon nanotubes, graphene, and quantum dots are used less often in nanomedicine [198-200]. Most of these nanomedicines are delivered via intraperitoneal injection, followed by oral, ocular, or other topical methods. When examining the size of nanoparticles in these nanomedicines, it is noted that the majority are smaller than 300 nm, with a few using particles ranging from 300 to 1,000 nm as carriers. It is important to note that in the synthesis of nanomedicines, the new properties that emerge in other areas of nanotechnology at dimensions below 100 nm (such as quantum size phenomena) are generally not of much interest, except in specific cases like quantum dots [201-203]. Therefore, the typical size range of 1 - 100 nm, as defined in nanotechnology, does not apply to nanomedicine. What is crucial in nanomedicine is 2 folds: The ability to transport sufficient amounts of drugs, which can increase the size of the carrier, and the precise control over the connection and arrangement of biomolecules (molecular dimensions). This precise control of molecular dimensions is a key feature of nanotechnology, granting nanomedicine its unique therapeutic properties and effects [204-207].

CNTs (long sheets of graphene rolled into cylindrical shapes) are the most studied carbon allotrope for biosensing purposes, and electrodes functionalized with CNTs can be used for aptamers, molecularly imprinted polymers (MIPs), proteins, nucleic acids, etc. It can easily bind to various receptors such as (**Table 1**). To conjugate CNTs and receptors, various compounds such as cysteamine, ethyl(dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (NHS), (3-aminopropyl) triethoxysilane (APTES), and glutaraldehyde were used. The chemistry of coupling is being studied. The choice of receptor and the chemistry used for its immobilization play an important role in the properties of the sensor. In a comparative study using aptamers, MWCNTs showed a 10-fold higher sensitivity to pandemic H1N1 compared to antibodies. This swine flu virus strain is responsible for seasonal influenza attacks. Among the various forms of carbon, most of the research on biosensor development has been conducted on carbon nanotubes [208-211]. **Figure 4** shows his 2 general methods for surface modification of carbon nanotubes used for virus detection. Functionalized carbon nanotube electrodes can easily bind a variety of receptors, including aptamers, molecularly imprinted polymers (MIPs), proteins, and nucleic acid. To date, several coupling agents such as cysteamine, ethyl (dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (NHS), (3-aminopropyl) triethoxy silane (APTES) and glutaraldehyde have been the coupling of carbon nanotubes to receptors has been studied [31-33]. The choice of receptor and the chemistry involved in its establishment play a very important role in the diagnostic properties of the final product. Therefore, multi-walled carbon nanotubes conjugated with aptamers are 10 times more susceptible to H1N1 (seasonal influenza) than antibodies. Functionalization of carbon nanotubes can also significantly change the detection capabilities of these nanostructures [34-35]. Carbonylated carbon nanotube-based viral sensors are highly specific for the Zika virus, which causes Zika fever. Carbon nanotubes with amide groups have higher electrochemical stability and better electron transfer through the amide bond and moiety containing -NH_2 groups. The application of this system is electrochemical screening for Zika virus and dengue fever by testing for the presence of nonstructural glycoprotein NS1 in serum and urine samples. Aminated carbon nanotubes are also used to detect important serum markers of hepatitis. Another approach to modify the surface of carbon nanotubes is to dope them with

metal nanoparticles, as shown in **Figure 5**. For example, dispersion of gold nanoparticles on multiwalled carbon nanotubes results in enzyme-like peroxide activity [36-39]. This structural change improved the sensitivity of this sensor for H_3N_2 virus detection by approximately 500 times compared to conventional chromatography kits. The detection limit of this sensor is also 385 times lower than that of ELISA. In general, the presence of nanoparticles in carbon nanotube nanocomposites provides 4 major benefits: 1) A stronger electrochemical reaction is achieved due to the synergistic effect of electronic interactions. 2) Receptor binding by hydrogen bonds, π-π interactions, and electrostatic forces. 3) increased surface area improves surface adsorption of analytes and 4) improves biocompatibility [40-43]. Graphene is the second most commonly used form of carbon in virus detection systems. Research shows that SARS-CoV-2 graphene-based sensors are approximately 40,000 times more sensitive than ELISA and specific for MERS-CoV, which is structurally similar to SARS-CoV-2. **Figure 6** shows the detection of SARS-CoV-2 virus using a graphene-based field-effect transistor (FET) sensor. The presence of the virus causes a change in the surface potential of the channel. When the protein binds to the immobilized antibody, an electrical response is generated. Among 2-dimensional forms of carbon, reduced graphene oxide (rGO) is considered the most desirable nanomaterial for virus detection due to its crystal defects, heteroatomic impurities, and low cost. Reduced graphene oxide is produced by reducing graphene oxide through electrochemical, chemical, or thermal processes. The reagents used for reduction determine the carbon to oxygen ratio and crystal defects that affect the electrochemical properties of the product. Reduction with ascorbic acid produces rGO with properties used in the diagnosis of meningitis virus and Japanese encephalitis virus. Zero-dimensional deformation of carbon is one of the nanostructures that has attracted great attention in recent years due to its special electrical and optical properties, such as photoluminescence, chemiluminescence, and electrochemiluminescence for virus detection. **Figure 6** shows the application of thiolates graphene quantum dots to detect hepatitis C virus.

Noble metal nanoparticles have significant plasmonic, catalytic and electronic properties. They can interact with various biological molecules such as oligonucleotides, aptamers and antibodies. Nanostructures such as gold nanoparticles are biologically ineffective, and with this feature, they are suitable options for the establishment and stabilization of proteins without the possibility of denaturation. Gold nanoparticles are the most widely used inorganic Nanostructures for virus detection. These nanoparticles have been used a lot, especially in the detection of SARS-CoV-2. For example, a kit containing gold nanoparticles produced in yeas 2020 detects SARS-CoV-2 within 15 min and with an amount of 10 - 20 μL of blood serum. Tamiflu is an antiviral drug known by the generic name of oseltamivir, and resistance to it is especially important and dangerous in patients with blood malignancies. **Figure 7** shows how the system based on gold nanoparticles works in the detection of influenza virus resistant to Tamiflu. Magnetic nanoparticles, quantum dots, silver nanoparticles, and silicon-based nanoparticles are other inorganic Nanostructures that have been evaluated and used to detect viruses. Organic frameworks, including covalent organic frameworks (COFs) and organic-metallic frameworks (MOFs), dendrimers and molecular template polymer nanoparticles are considered to be the most important organic Nanostructures in the field of virus detection.

Table 1 CNTs for virus detection.

Nanomaterial	Platform	Receptor type	Target	Method	Limit of detection
Multi-walled carbon nanotube/ zeolite nanocrystal	[92]	[92]	[92]	[92]	5×10^{1} COPIES mL^{-1}
Aminated carbon nanotubes	[93]	[92]	[93]	[93]	3.4×10^{1} pg mL^{-1}
Multi-walled carbon nanotube/ Chitosan	[33]	[33]	[33]	[33]	8.3×10^{1} fg mL^{-1}
Multi-walled carbon nanotube/ Chitosan	[32]	[32]	[32]	[32]	167×10^{-2} fg mL^{-1}

Nanomaterial	Platform	Receptor type	Target	Method	Limit of detection
Multi-walled carbon nanotube	[94]	[94]	[94]	[94]	13×10^{-1} nm
Semiconducting single-walled carbon nanotube	[95]	[95]	[95]	[95]	2×10^{1} pm
N-doped multi-walled carbon nanotube	[96]	[96]	[96]	[96]	2.0 pm
Single-walled carbon nanotube/ 1-pyrene methylamine	[97]	[97]	[97]	[97]	840.00 $tcld_{50}$ mL^{-1}
Carbon nanotubes	[98]	[98]	[98]	[98]	167×10^{-2} fm
Carbon nanotubes	[99]	[99]	[99]	[99]	1.0 pm
Magnetic multi-walled carbon nanotube	[99]	[99]	[99]	[99]	84×10^{-1} pm
Magnetic multi-walled carbon nanotube	[100]	[100]	[100]	[100]	88×10^{-1} pm
Multi-walled carbon nanotube	[101]	[101]	[101]	[101]	34×10^{-1} pfu mL^{-1}
Gold nanoparticles/ multi-walled carbon nanotube	[102]	[102]	[102]	[102]	3×10^{2} fg mL^{-1}
Gold nanoparticles/ multi-walled carbon nanotube	[102]	[102]	[102]	[102]	10.0
Gold nanoparticles/ multi-walled carbon nanotube	[102]	[102]	[102]	[102]	10.0
Gold nanoparticle/ carbon nanotube	[103]	[103]	[103]	[103]	$8.60\times10^{+2}$ pg mL^{-1}

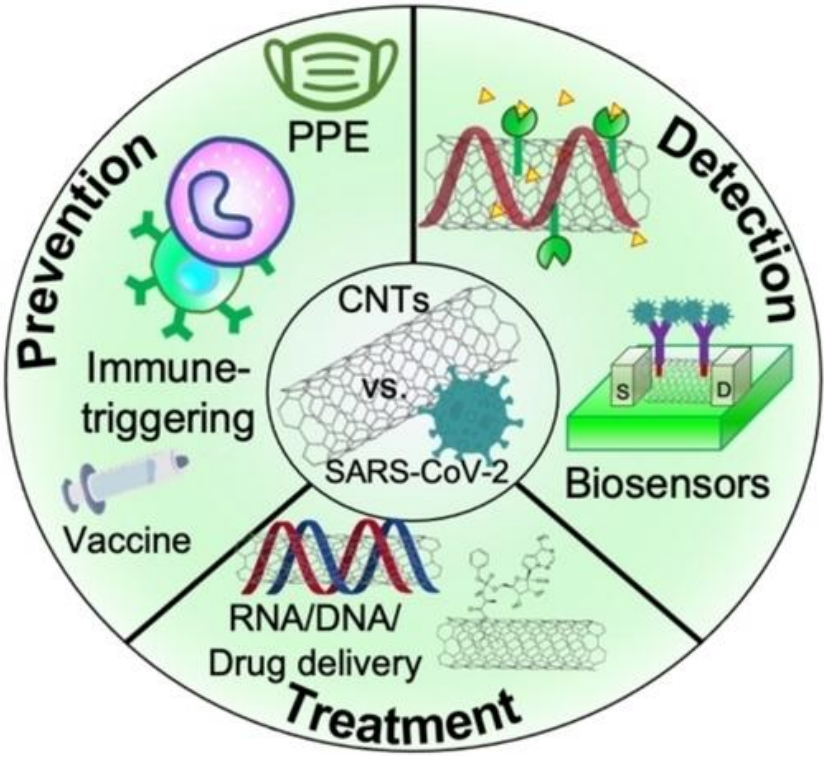

Figure 4 The most common methods of modifying carbon nanotubes for use in virus detection [34].

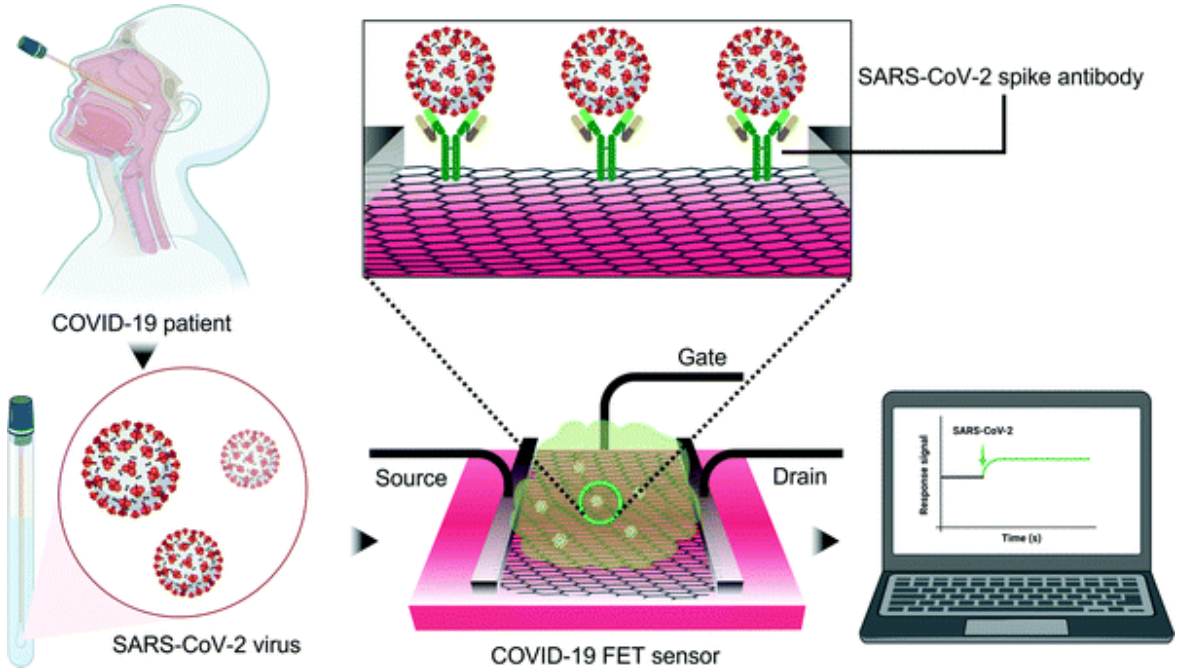

Figure 5 The most common methods of modifying carbon nanotubes for use in virus detection [41].

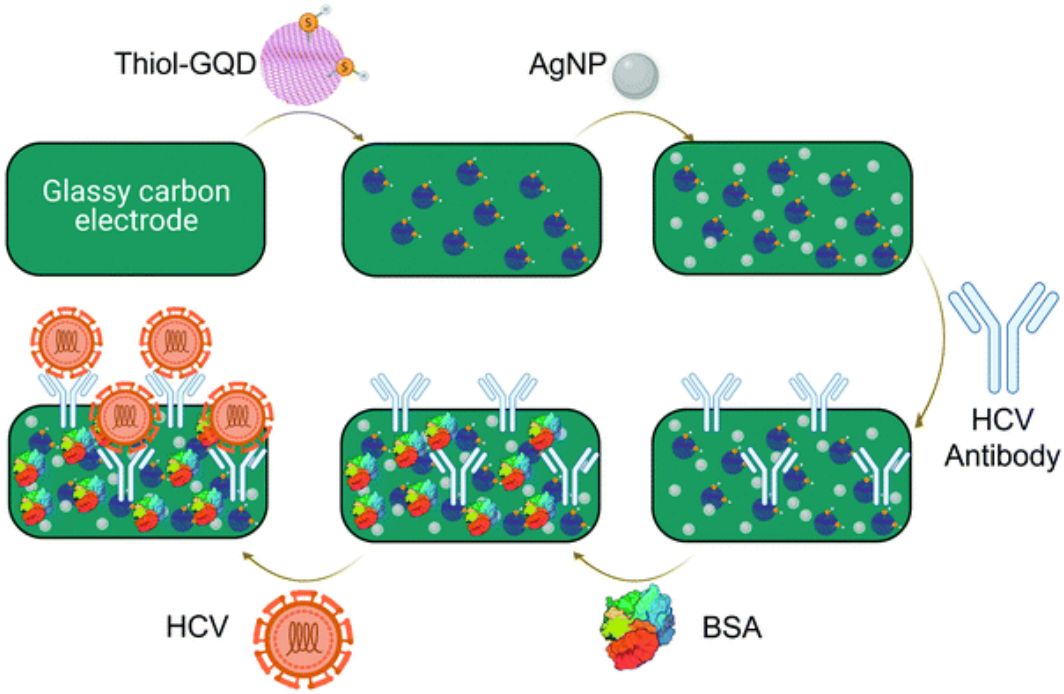

Figure 6 Thiolates graphene quantum dots for detection of hepatitis C virus [42].

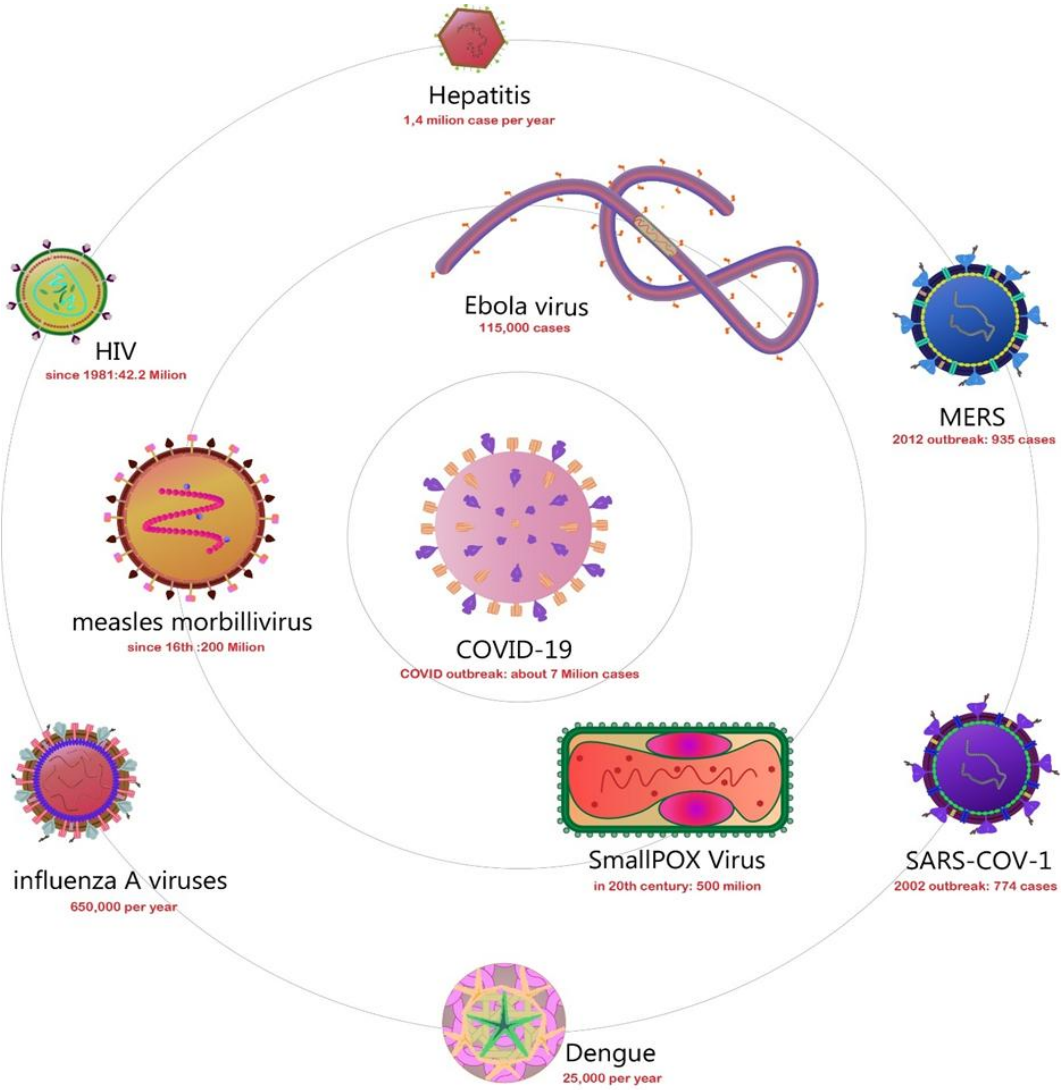

Figure 7 Identification of influenza virus resistant to Tamiflu with the system based on gold nanoparticles [53].

Tracking viruses

In spite of the fact that natural fluorophores such as cyanine, coumarin, and rhodamine are still utilized for imaging purposes, their outflow concentrated diminishes when uncovered to light, which is called photobleaching. By expanding the concentrated of the light utilized, a drop in fluorescence escalated is watched, which decreases the settling control, retrievability and steadiness [209-213]. Carbon and Nanostructures with sp^3 hybridization, such as fluorescent nanodiamonds, have steady fluorescence within the near-infrared (NIR) run. This fluorescence is direct in a wide run of concentration and is exceptionally safe to the impedances of non-specific biomolecules. Compared to the broadly utilized quantum specks, fluorescent nanodiamonds are non-toxic and photostable. **Figure 8** appears the following of bacteriophage utilizing fluorescent nanodiamonds [214-216]. In **Figure 8** (blend of target (dark) and non-target (yellow) bacterial species is watched. portrays the connection of the nanodiamond-bacteriophage match to the target microbes. In **Figures 8**, the ruddy color appears the fluorescent nanodiamonds, the blue color appears the bacteriophage, the dark color appears the target microbes, and the yellow color appears the non-target microbes. The nanodiamond-bacteriophage combine ties to the receptor on the layer of the target microbes (dark), so no authoritative is watched between the demonstrated match and the non-target microbes (yellow). Quantum dots and metal nanoparticles are inorganic Nanostructures in the field of virus detection. **Figure 9** shows fluorescence imaging of separation of

HIV RNA from capsids (red) labeled with CdTe: Zn^{2+} quantum dots (green). Scale bar corresponds to 1 μm. For example, the elucidation of HIV was recently studied by labeling the RNA with red His Zn^{2+}-doped CdTe QDs and the capsid with a green organic arsenic dye, as shown in **Figure 10**.

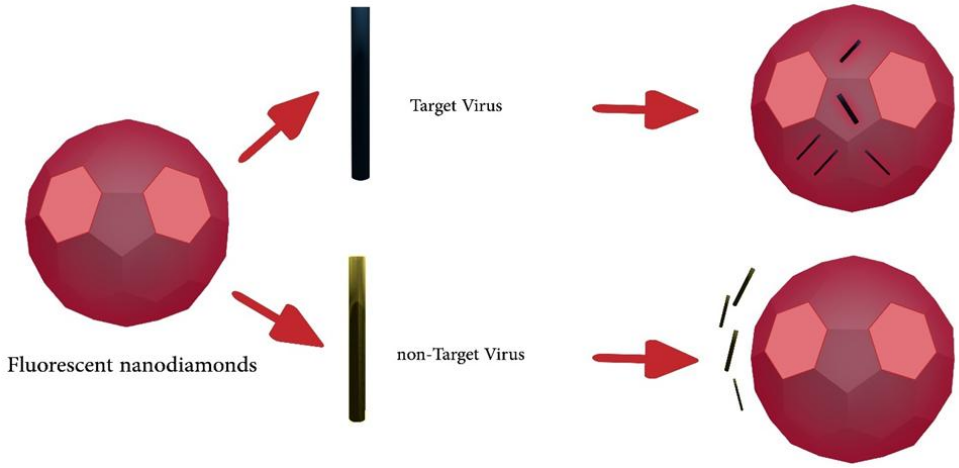

Figure 8 Bacteriophage tracking using fluorescent nanodiamonds [49].

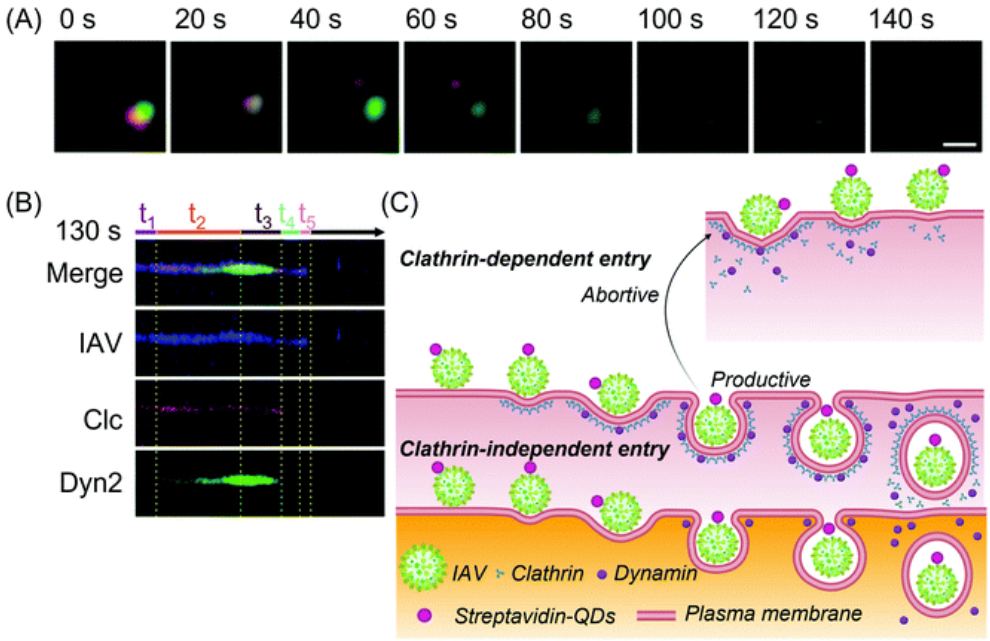

Figure 9 Images of dynamic dissociation of RNA labeled with quantum dots (green) from capsid (red) [54].

Inorganic nanostructures in the detection and tracking of viruses

Nanomedicine is a developing investigate field where nanoscience is utilized to create biomedical devices to realize progressed atomic diagnostics, gene/drug delivery/discovery frameworks, and bioimaging methods. Nanostructures of distinctive sizes and shapes with particular physicochemical properties donate rise to an assortment of nanoscale morphologies counting nanopores, nanospheres, nanoclusters, empty circles, yolk-shells, nanorods, nanotubes, nanowires, core-shells, etc. [217-221]. These nanostructures can be made of metals, metal oxides, amalgams, carbon, and other sorts of natural materials. Among these nanomaterials, silica nanoparticles (SNPs), gold nanoparticles (GNPs), quantum dabs (QDs), carbon-

based and biopolymer nanostructures are the foremost commonly utilized sorts within the field of nanomedicine. In comparison, each has particular applications with preferences and impediments. For illustration, silica nanostructures are commonly utilized as carriers for medicate stacking, whereas gold nanoparticles are utilized with photothermal specialists, particularly in cancer treatment and biosensing. Quantum dabs, on the other hand, are known for their applications in biosensing due to their fluorescent properties [222-225]. The superparamagnetic properties of attractive nanoparticles (MNPs) make them reasonable as imaging apparatuses in attractive reverberation imaging (MRI). For antigen delivery, various inorganic nanostructures have been investigated. Most of these nanostructures are not biodegradable, but their advantage over other nanostructures is that they can be synthesized in different and controlled shapes and sizes. Gold nanoparticles are one of the nanoparticles that have many applications in this field. One of the advantages of these nanoparticles, in addition to the possibility of controlled synthesis, is the possibility of functionalizing the nanoparticles with carbohydrates [226-228].

Intermediate and internal intermediate elements have d and f orbitals, respectively, that are not completely filled with electrons. These orbitals contain high-energy electrons that are responsible for the mineral's magnetic, photoelectronic, and quantum properties. These capabilities can be used in diagnostic and imaging systems as well as through 3 approaches: (1) by manipulating and tuning the physical properties of Nanostructures, such as size and shape, and (2) by attachment. can be used to best adapt it for use in the sensing field. generate appropriate functional groups and (3) combine with other n Nanostructures to produce multifunctional nanocomposites (**Figure 10**).

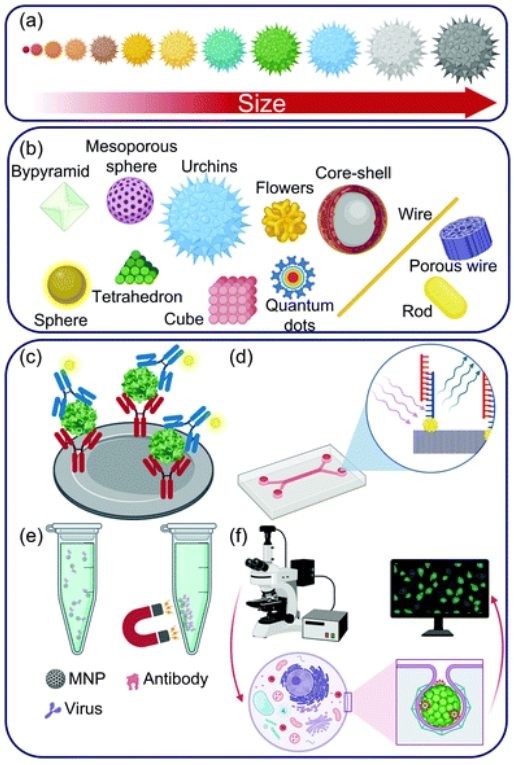

Figure10 Inorganic nanostructures in the detection and tracking of viruses [50-52].

Nonporous silica nanoparticles (NSNs)

Nonporous silica NPs are one of the foremost critical sorts of silica nanoparticles and have pulled in awesome intrigued in nanobiotechnology. The surface silanol bunches (-Si-OH), which are continuously show on the surface of silica nanoparticles, can be effectively functionalized with amine and/or carboxyl bunches. This handle comes about in NSNs with positive,

negative, or zwitterionic surface charges. The surface charge and surface chemistry of NSNs play a key part in deciding the interaction of nonporous silica nanoparticles with different biomolecules (e.g., DNA, proteins and drugs) and cells. A few one-of-a-kind properties of NSNs have been detailed, counting their hydrophobic surface, exceedingly controllable measure and shape, effortless surface functionalization, tall mechanical inflexibility, and effortless large-scale union [229,230]. Moreover, various biomedical applications of NSNs in hydrophobic sedate conveyance frameworks have been recognized, as well as the utilize of NSNs in quality and little particle conveyance and protein embodiment forms. Different proteins and drugs can be typified in NSNs through in situ blend strategies. Copper-zinc superoxide dismutase, cytochrome c, and myoglobin were typified in straightforward quartz glass without noteworthy misfortune of structure and work. As specified over, NSNs as a carrier stage for protein and peptide biopharmaceuticals not as it were having progressed soundness, restorative potential, bioavailability, and physicochemical properties, but moreover have less side effects. In most of the past ponders, there are 2 common techniques for medicate consolidation into the silicon network of nonporous silica nanoparticles: (a) epitome and (b) covalent authoritative. In covalent holding, drugs are covalently joined to siloxane bunches through degradable ester bonds. Be that as it may, epitome procedures incorporate covalent connection of drugs to silica networks by co-condensation with tetraethyl orthosilicate (TEOS) through the Stöber strategy. Diminished pH values moderate down the corruption of silica nanoplatforms, coming about within the slow discharge of encapsulated drugs. Spearheading work within the improvement of dye-encapsulated particles was synthesized by the Benezra gather by typifying Cy5 color onto adjusted Stöber-like silica nanoparticles coated with polyethylene glycol (PEG) atoms. The PEG particles were conjugated to ^{124}I- cRGDY (cyclic arginine-glycine-aspartic corrosive) peptide ligands that target αvβ3 integrin [229-232]. The peptide ligands were at that point labeled with positron-emitting radionuclides using tyrosine linkers to produce signals that may well be quantitatively imaged utilizing positron outflow tomography (PET) (**Figure 11**). The ^{124}I- cRGDY-PEGylated silica nanoparticle specks have been affirmed for first-in-human clinical trials as powerful cancer focusing on tests.

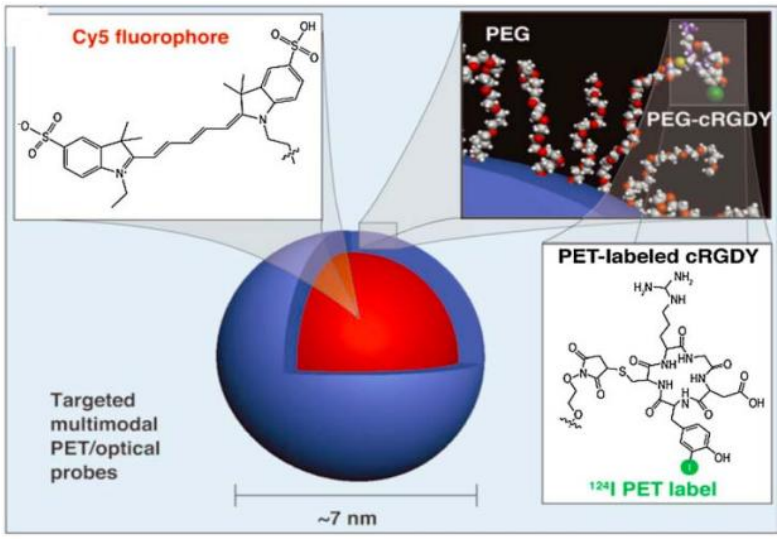

Figure 11 Schematic of ^{124}I-cRGDY-PEGylated core-shell silica nanoparticles with radiolabels and peptides on the surface and reactive dye molecules containing core [20].

Mesoporous silica nanoparticles (MSNs)

Mesoporous silica nanoparticles are promising candidates for novel medicate conveyance frameworks. Expansive inside surface region, greatly tall pore volume, controllable morphology (estimate and shape), biocompatibility, simple amalgamation, and simple

surface functionalization are among the key properties for different applications in nanomedicine, particularly as nanocarriers for medicate conveyance frameworks [233,234]. Improved discharge of charged drugs by cap uniting is one of the outstanding properties that creates mesoporous silica nanoparticles utilized as a methodology to plan sedate conveyance vehicles. A common incitement strategy is based on GSH-triggered medicate discharge (redox response framework). In this methodology, the disulfide bond between the capping operator and the surface silanol bunches of MSNs is diminished by intracellular GSH, in this manner expelling the capping operator and discharging the consolidated medicate. Their consider concluded that the length and conclusion gather of the ligands may influence the medicate capping and discharge productivity. Besides, the sum of ligands on the MSN surface and the connection of the ligands to β-CD (as conclusion caps) are 2 critical parameters that are influenced by the surface scope, medicate stacking capacity, and discharge rate. The discharge component of β-CD capped and DOX stacked MSNPs was activated by GSH. The pH-controlled decamping strategy is another common procedure for specific sedate discharge in cancer cells. In rundown, they appeared that ZnO QD caps on MSNs may viably stifle the discharge of charged DOX at undesired locales. At the same time, the ZnO QD caps broken down in the acidic environment (lysosomal pH) of cancer cells activated the discharge of medicate cargo from the pores of MSNs into the cytosol (**Figure 12**). Superparamagnetic press oxide nanoparticles (SPIONs), CdS nanocrystals, and (G2)-PAMAM dendrimers are other cases of caps that have been utilized for the controlled discharge of different drugs. In general, focused on conveyance frameworks based on polymeric nanoparticles as medicate carriers speak to an exceptional course to cancer treatment [233-235]. The most highlights of this framework are non-toxicity, biodegradability, long circulation, biocompatibility, and a wide extend of helpful medicate stacking capacity. Other vital perspectives incorporate shape characteristics and particular measure for tissue entrance by dynamic and detached focusing on, particular cellular/subcellular trafficking pathways, and simple control of cargo discharge through progressed fabric building

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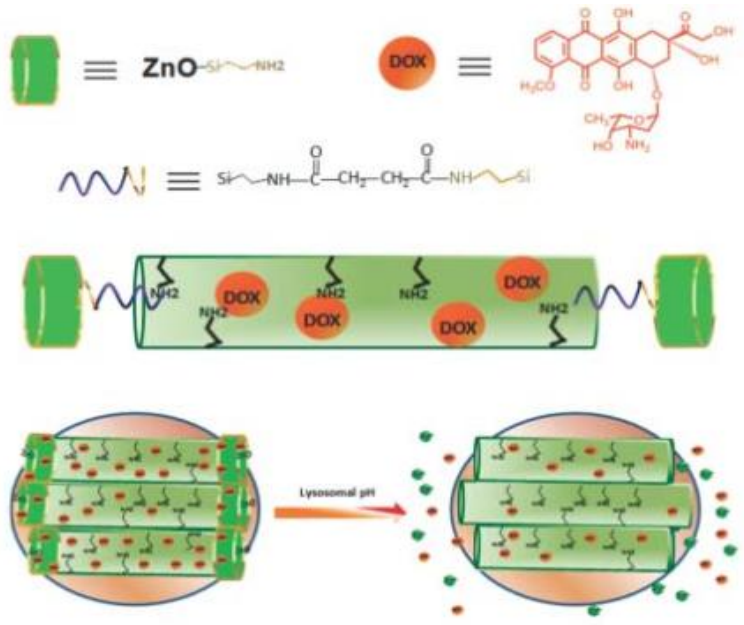

Figure 12 Graph of ZnO@MSNs-DOX. Mesoporous silica nanoparticles are stacked with cationic anticancer medicate doxorubicin and beautified with amine-functionalized ZnO nanoparticles. Within the acidic environment of cancer cells, the ZnO caps are corrupted and the doxorubicin sedate is discharged from the pores into the cancer cells [28].

Quantum dots

Quantum dots, too known as colloidal semiconductor nanocrystals, are characterized as gems of fluorescent semiconductor materials composed of iotas of II-VI or III-V components and with distances across of as it were 10 - 100 particles (2 - 10 nm).

Basically, Quantum dots comprise of closed core-shell arrangements with a center (as a rule made of CdS, CdSe and CdTe) and a shell (more often than not made of ZnS, ZnCd and CdS). For the most part, the in general estimate of these core-shell Nano assemblies is little, with distances across extending from 4 to 12 nm (**Figure 13**). Due to their special inborn properties such as tall brightness, long perseverance, wide and persistent assimilation range, contract emanation range, and tall fluorescence quantum abdicate, they are broadly utilized to create optical tests for bioassays [236,237].

Figure 13 Schematic of the core-shell arrangement of Quantum dots. The center is ordinarily composed of CdS and CdSe, whereas the shell is ordinarily composed of ZnS, ZnSe, and CdS [38].

Gold nanoparticles

Colloidal gold nanomaterials (e.g., nanorods, nanocages and nanocubes) of different sizes and shapes are reasonable as nanocarriers for biomedicine and medicate conveyance. Their ease of arrangement, soundness, moo cytotoxicity, and tall light termination coefficient from the obvious to near-infrared run make them vital candidates for the improvement of anticancer drugs and nanocarriers. Au nanorods (NRs) have been utilized for laser-induced hyperthermia treatment of cancer cells due to their NIR retention properties. The one-of-a-kind properties of gold nanoparticles permit them to be functionalized with different biomolecules such as proteins, antibodies, and different biomarkers. Within the past 2 decades, their high molar termination coefficient within the unmistakable to near-infrared run and surface plasmon reverberation (SPR) have made them fabulous photothermal specialists in biosensing of different biomolecules in cancer treatment and helpful applications. Additionally, gold nanoparticles are perfect nanocarriers for reversible authoritative of hydrophilic and hydrophobic drugs. Doxorubicin (Dox) and pyrene (Pyr) were typified into Au NP-lysozyme total particles by the Khandelia bunch as hydrophilic and hydrophobic show particles, individually. The comes about show that the novel nanocarriers arranged based on Au NP-lysozyme totals have fabulous potential for medicate stacking and discharge forms and can act as multimodal sedate conveyance vehicles [238,239]. In the meantime, Au NPs have been appeared to be compelling operators for photodynamic treatment. By covalently conjugating anti-HER2 monoclonal antibodies to PEG-gold nanoparticles, a quaternary photodynamic operator (antibody-zinc phthalocyanine-PEG-GNP) was arranged and utilized as a potential operator for focused on photodynamic cancer treatment of breast cancer. Besides, gold nanoparticles have been displayed as a successful stage for identifying foodborne pathogens. For case, a novel antibody/GNP/magnetic nanoparticle nanocomposite was utilized to identify the foodborne pathogen Staphylococcus aureus in drain. The arranged nanocomposite (antibody/AuNP/MNP) was synthesized from BSA (bovine serum albumin)-coated attractive nanoparticles, and after that gold nanoparticles and anti-Staphylococcus aureus antibodies were adsorbed onto the surface of the BSA-coated MNPs. Gold nanoparticles (AuNPs) are appropriate for creating and examining organic intuitive. The surfaces of these particles can be customized utilizing thiol-based ligands that tie firmly to the gold

surface. For little particles, monolayers of reasonable shapes can be made, permitting chemical control over the surface by making uniform, blended monolayer particles. Bigger particles can be functionalized in a comparative way; be that as it may, their surface structures are inalienably less requested and have ligands and ionic species on the surface. Besides, essential gold is non-toxic, meaning that experiences picked up with AuNPs can be specifically exchanged to real-world applications. AuNPs are too utilized as names in atomic acknowledgment and characterization conventions for in vitro applications. In *in vivo* methods, AuNPs have been appeared to be carriers of restoratively dynamic compounds, reasonable for multitargeted surface functionalization with tall fondness and specificity for cancer cells, and have appeared a tall capacity to at the same time oblige helpful and imaging specialists, coordination them into a capable theragnostic stage. Radiotherapy (RT) is ordinarily utilized to treat cancer with ionizing radiation. The extreme point of RT is to kill anomalous cells whereas saving sound tissue. Targeted RT utilizing gold nanoparticles (GNPs) is being explored as a implies to encourage make strides the therapeutic rate of RT [240].

Magnetic nanoparticles

Magnetic nanoparticles (MNPs) with superparamagnetic properties are a special type of inorganic nanomaterials that can be used as contrast agents in magnetic resonance imaging (MRI), for site-specific gene and drug delivery, and as diagnostic agents in the presence of external magnetic fields. Their special physical and chemical properties make them ideal materials for biological research. Superparamagnetic iron oxide nanoparticles (Fe_3O_4 and Fe_2O_3), gadolinium oxide nanoparticles (Gd_2O_3), and manganese-based nanoparticles (MnO, Mn_3O_4, etc.) are the most commonly used MNPs that have attracted great interest in clinical MRI. To make these MNPs biocompatible for biological applications, they are usually coated with various water-soluble molecules such as cationic polymers (PLL, PEI, etc.), cationic lipids, and dendrimers (polyamidoamine, PAMAM, etc.). For target-specific delivery, MNPs can be conjugated with appropriate biomolecules such as antibodies and positively charged amino acids to increase the uptake of MNPs by tumors. Moreover, it can improve the selectivity and intracellular transport of magnetic nanoparticles. reported biocompatible iron oxide MNPs conjugated with the antibody J591 targeting prostate-specific membrane antigen (PSMA) to improve MRI of prostate cancer [230-235]. This study shows that PSMA-targeted MNPs can significantly increase the magnetic resonance contrast of prostate tumors compared with MNPs alone (non-targeted MNPs). This study shows that PSMA-targeted MNPs can significantly increase the magnetic resonance contrast of prostate tumors compared with MNPs alone (non-targeted MNPs)[236-238].

Organic nanostructures used for virus detection and tracking

Organic nanostructures used for virus detection and tracking are typically polymeric in nature, their synthesis is cheap and simple, and they are stable over a wide temperature range. properties that they can easily bind and coordinate with metals and create porous scaffolds, they exhibit exceptional fluorescence and can serve as substrates for establishing sensor receptors [241-243]. Equipped with: Organic Nanostructures themselves can also act as receivers or sensor transducers. Many of these nanostructures are naturally neutral and biocompatible in the environment (**Figure 14**).

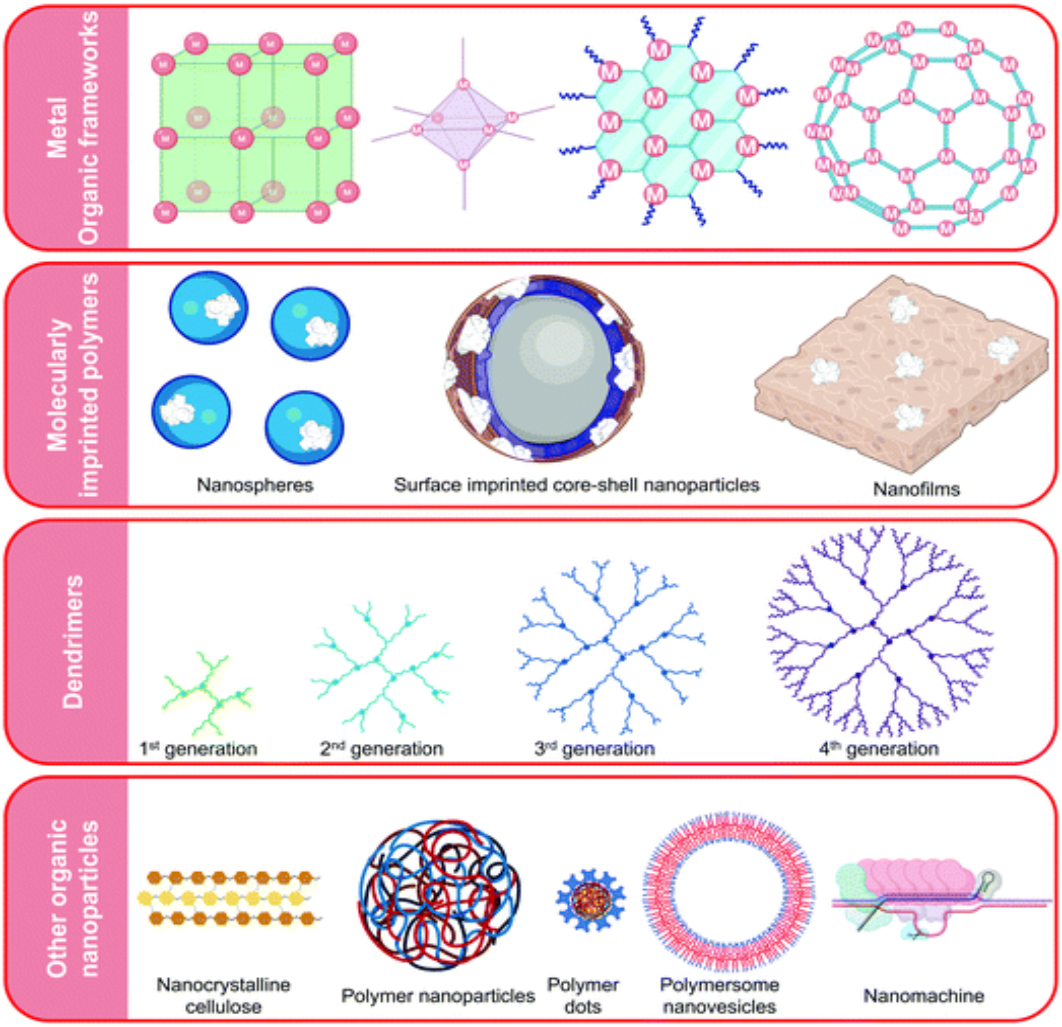

Figure 14 Organic nanostructures in the detection and tracking of viruses [107].

Organic frameworks

COFs are porous polymer nanostructures. They have excellent thermal stability and low density. However, due to the lack of high-energy electrons, they have only been used once for virus detection. In this study, a 3.5 nm COF layer was integrated with AuNP and Ag nanocluster labeled DNA for the measurement of HAV and HBV. Meanwhile, MOFs are the most commonly used organic nanomaterials for virus detection [244]. They have a high surface area to volume ratio and the pore size can be easily modified. MOFs are essentially coordination polymers in which organic components bind metal ions to form complex structures. Biosensors use 1- to 3-dimensional MOFs, or a combination of several variants. 1D zinc carboxylate MOFs with aromatic bipyridine peripheral ligands are water-soluble and allow nanomolar sensing, but at the expense of long test times. In a comparative study of zwitterionic zinc carboxylate MOFs, it was observed that 2D MOF nanosheets interacted with the probe DNA more efficiently than 1D nanochains, 2D networks, and 3D polymer matrices [245,246]. The use of 2D copper MOFs reduced the LOD by an order of magnitude. The 3D copper MOF (**Figure 15(A)**) can also be used as a nanoreactor for the copper-mediated azide-alkyne cycloaddition "click reaction" in a time-resolved fluorescent immunoassay of HBV surface antigen (**Figure 15(B)**).

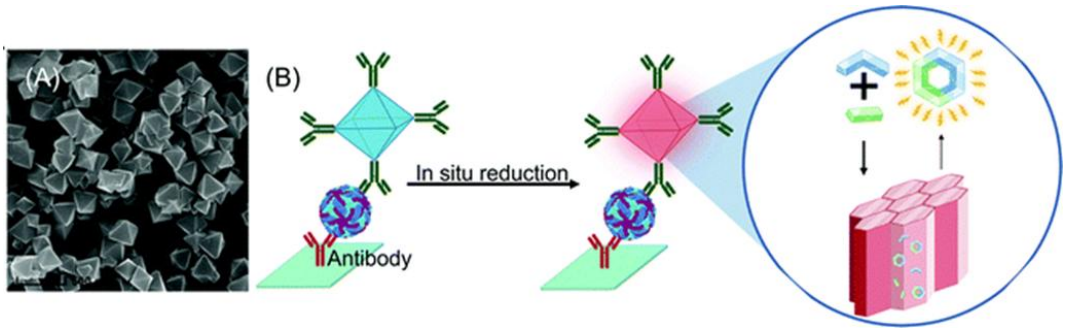

Figure 15 (A) SEM image of copper-organic framework. (B) 3D nano-copper-organic framework structure for detecting Hepatitis B virus [107].

Molecularly imprinted polymeric nanoparticles

Molecularly imprinted polymer nanoparticles (MIP-NPs) are nanoparticles prepared by polymerization of 1 or more functional monomers in the presence of a template molecule. Removal of the template molecule then reveals target-specific, high-affinity nanocavities that provide a cheap, long-lasting alternative to antibodies [247,248]. MIP-NPs have emerged as promising nanomaterials for virus detection due to their ease of synthesis and resistance to extreme environments. Selection of appropriate functional monomers is critical for the development of assays with high sensitivity and rapid response (**Table 2**). For example, in the case of MIP-NPs for RLS-based HAV detection, (dimethylamino)ethyl methacrylate produced a pH-responsive polymer with a significantly lower LOD (100 fM) and response time (20 min) than N-isoacrylamide (LOD: 1.1 pM, response time: 30 min) or dopamine (LOD: 6.2 pM, response time: 150 min). Computer modeling allows us to select functional monomers with the highest binding affinity to the target, thus significantly reducing experimental costs and research time. *In silico* design can also be used to select the most stable viral epitope as the template peptide to avoid the pitfall of template loss during rebinding [249]. Such MIP-NPs (65 nm) are resistant to hydrolytic enzymes, similar to monoclonal antibodies; however, unlike most antibodies, MIP-NPs can be easily regenerated and reused multiple times. The virus detection mechanism is also a key parameter for improving the sensor performance. For example, for JeV imprinting with APTES, an almost 12-fold higher sensitivity was reported when replacing RLS with a fluorescence-based measurement. Replacing APTES with zinc acrylate as the functional monomer and adding polyethylene glycol as a passivation agent expanded the detection range by 7-fold and increased the imprinting factor by 2.5-fold [250].

Table 2 MIP-NPs for virus detection.

Functional monomer	Size (nm)	Template type	Target	Method	LOD
NIPAam, BIS, TBAm and AAc	205 - 238	Virus	[72]	[72]	[72]
Dimethylaminoethylmethacrylate	13	//	[191]	[191]	[191]
NIPAam, TBAm, BIS, NPhAam and TFMA	65	Epitope	[192]	[192]	[192]
APTES and TEOS	421	Virus	[193]	[193]	[193]
APTES and TEOS	15	//	[194]	[194]	[194]
APTES and TEOS	200	//	[195]	[195]	[195]
Dopamine	200	//	[196]	[196]	[196]
Dopamine	70	//	[197]	[197]	[197]

Functional monomer	Size (nm)	Template type	Target	Method	LOD
NIPAam	110	//	[198]	[198]	[198]
Thiophene	200	//	[121]	[121]	[121]
Zinc acrylate	50	//	[126]	[126]	[126]
2,2':6",6" terpyridine, EGDMA	< 100	Lead	[199]	[199]	[199]

Conclusions and future prospects

For some Nanostructures, the particle size is smaller than the wavelength of the constituent electrons, which occurs during quantum coagulation when fluorescent nanoparticles bind. These nanoparticles are photostable and resistant to photobleaching, making them well-established materials for non-invasive observation of disease spread. Nanomaterial-mediated SVT leads to the disruption of disease internalization pathways and their replication, which may be a prerequisite for acquiring beneficial conversations. Fluorescent nanoparticles have become a promising option, with tricky and outrageous names such as "green fluorescent protein." Additionally, high-throughput curing screening is enabled, reducing processing and experimental costs. Nanoparticles have also been used in imaging techniques to test the viability of developing microscopy strategies to track contamination. As the size and dielectric constant of virus-mimetic nanoparticles are similar to those of the disease, the virus-mimetic nanoparticles will continually replace the virus-like particles within the host-guest system inside the cell. Based on the subsequent developments in contamination research, we can expect nanoparticles such as fluorescent names qubits, gold nanoparticles, and nanodiamonds to contribute to a large part of the imaging and internalization of diseases.

The use of Nanostructures has many positive effects on the performance of virus sensors, including improving sensitivity, having a specific function, shortening the response time, and being able to be used in complex environments.

In this survey we have concluded that the treatment of the viral contamination and current covid 19 incorporates the combination treatment of antiviral drugs and the resistant modeling drugs. Utilize of the antiviral drugs for the treatment of viral disease anticipates from sickness and as well as mortality rate. Parcel of clinical trials are going on to demonstrate their adequacy against SARS-CoV-2 and will certainly demonstrate to be productive and offer assistance to spare the human community.

In this review, we have presented recent studies on the application of nonporous silica nanoparticles, mesoporous silica nanoparticles, quantum dots, gold nanoparticles, and magnetic nanoparticles as therapeutics in sensing and drug delivery. However, there are also some organic nanomedicines approved by the FDA. Only a few inorganic nanoparticle-based nanomedicines approved by the FDA have been used in clinical practice. As most inorganic nanomedicines are still in the preclinical stage or at the cellular and intact animal levels, further research is needed to understand the possible interactions between inorganic nanomaterials and biological systems from a molecular perspective. Emerging nanotechnologies are contributing to the construction of drug delivery systems as a potential approach to overcome some of the obstacles to efficient targeting and treatment of cancer cells. However, significant efforts and innovation are required to overcome the challenges associated with the use of inorganic nanocarriers in sensing, clinical imaging, drug delivery, and therapy.

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