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Nanomaterials Fabrication in Additive Manufacturing

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ABSTRACT

Nanomaterials are substances that have at least one dimension that falls within the three-dimensional nanoscale range or fundamental structural components made of substances that fall inside this range. Micro-nano 3D printing technology can realize the processing of 3D micro-nano structures with nanometer precision and has broad application prospects in many fields. Metals and polymers can be easily connected through bonding reactions to obtain metal-metal or covalent bonds in 3D printing. These potent chemical bonds make 3D-printed structures stable, and 3D printing of metals and plastics is developing rapidly. The review focuses on the latest developments in unique composite nanomaterials for different field applications, comprising nanomaterials and 3D printing technology. A summary of the mechanisms, functional characteristics, benefits, drawbacks, and applications of various nanomaterials used in scientific 3D printing includes metal-based nanomaterials, metal-organic frameworks, upconversion nanoparticles, and lipid-based nanoparticles. Finally, this study presents an overview and highlights the issues that need to be resolved for nanomaterials to continue to be developed for the advantages of 3D printing.

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1. INTRODUCTION

Nanocomposites (NCs) have attained a cons The concept of nanotechnology was first proposed in 1959 by the famous Nobel Prize-winning physicist Richard Feynman [1]. The invention of the scanning tunneling microscope and fullerenes also popularized the term. The European Commission defines nanomaterials as powdery or clumpy natural or artificial materials consisting of basic particles with one or more three-dimensional dimensions between 1 nanometer and 100 nanometers. The total number of these basic particles accounts for more than 50% of all particles in the entire material [2]. According to the physical form division, nanomaterials can be roughly divided into five categories: nano powders (nanoparticles), nanofibers (nanotubes, nanowires), nano membranes, nano blocks, and nano phase separation liquids. Nanoparticles or artificial atoms with three- dimensions of the order of nanometers are called zero-dimensional nanomaterials, nanofibers are one-dimensional nanomaterials, and nano membranes (sheets, layers) can be called two-dimensional nanomaterials, and materials with nanostructures can be called three-dimensional nanomaterials [3]. At present, carbon nanotubes are one of the research hotspots of nanotechnology. Only nano powders have achieved industrial production (such as calcium carbonate, silica, zinc oxide, etc.), and other nanomaterials are still in the laboratory research stage.

3D printing technology, also known as additive manufacturing [4], has been widely used in various industries such as manufacturing, construction, biomedicine, and aerospace because it can produce components with complex shapes at a low cost. However, some applications are still limited, such as the moving parts of medical implants. 3D-printed metal materials are prone to metal fatigue and poor wear resistance and may eventually require a second operation to replace the relevant implant. Nano printing is an additive manufacturing technology that accumulates nanoparticles layer by layer to form nanostructures. Complex nanostructures can be constructed by controlling the size and position of nanoparticles. This technology has broad application prospects in nano device manufacturing and nanomaterial research. [5]

Recent review papers have discussed nanomaterials, 3D printing, and applications. Santos et al. [6] highlighted the potential for a partnership between nanotechnology and 3D printing for customized medicine. These publications were all primarily concerned with describing how the manufactured items might be employed in biomedicine. But as far as we know, they have yet to go into great detail about the uses and characteristics of nanomaterials in biomedical 3D printing. As a result, this study will give an overview and a fresh perspective on the aspects of these technologies while also incorporating the related uses of nanomaterials for 3D printing. The integration of 3D printing technology and nanomaterials is briefly described here, and we also go over the critical benefits of 3D printing. We conclude by outlining the difficulties and potential outcomes of fusing nanomaterials with 3D printing for different applications.

2. Three dimensional (3D) additive manufacturing Technologies

3D printing technology is a manufacturing method that builds entities layer by layer by superimposing materials [7]. Various additive manufacturing technologies are emerging with the continuous advancement of science and technology, bringing infinite possibilities to all walks of life. This article will introduce some standard nanomaterial-based additive manufacturing techniques.

Powder sintering is a standard technology in additive manufacturing, and its basic principle is to melt powder materials layer by layer to bond them into solid bodies. This technology is mainly applied to the manufacture of metal materials. Since metal has good thermal and electrical conductivity, metal parts of various complex shapes can be manufactured by melting powder and bonding those together [8]. Photocuring is an additive manufacturing technology that uses ultraviolet light or other light sources to cure liquid resins. In this process, liquid resin is cured layer by layer by shining a light source. This technology is suitable for manufacturing precision parts such as jewelry, models, etc. Since this technology can quickly manufacture objects of complex shapes, it is widely used in rapid prototyping [9]. Inkjet printing [10] is a common additive manufacturing technology, and its principle is similar to that of traditional inkjet printing technology. This technology sprays liquid material on the base plate through ink nozzles and solidifies it layer by layer. Complex three-dimensional structures can be created by carefully regulating the location of the inkjet and the curing procedure. Inkjet printing technology is widely used to make color models and artworks and is also used in the biomedical field to create artificial organs and tissue engineering materials. Electron beam melting [11] is an additive manufacturing technique that uses an electron beam to melt metal powder. This technology controls the irradiation position and power of the electron beam to melt the metal powder layer by layer and form a solid body. The electron beam has a high energy density and a small, heat-affected zone to produce high-density, high-strength metal parts. This technology is widely used in aerospace, automotive, medical, and other fields. Selective laser melting [12] is an additive manufacturing technique that uses a laser beam to melt metal powder. A laser beam can be focused to a specific location through a lens, melting the metal powder and solidifying it into a solid body. The technology is characterized by high precision and efficiency and is widely used in aerospace, medical, manufacturing, and other fields. Metal 3D printing based on selective laser melting technology can already produce metal parts with complex shapes and high performance.

The continuous development of additive manufacturing technology has brought significant changes and innovations to all walks of life. With the advancement of technology, additive manufacturing will play a more critical role in manufacturing, medical, aerospace, and other fields. It is believed that more advanced additive manufacturing technologies will emerge with the passage of time.

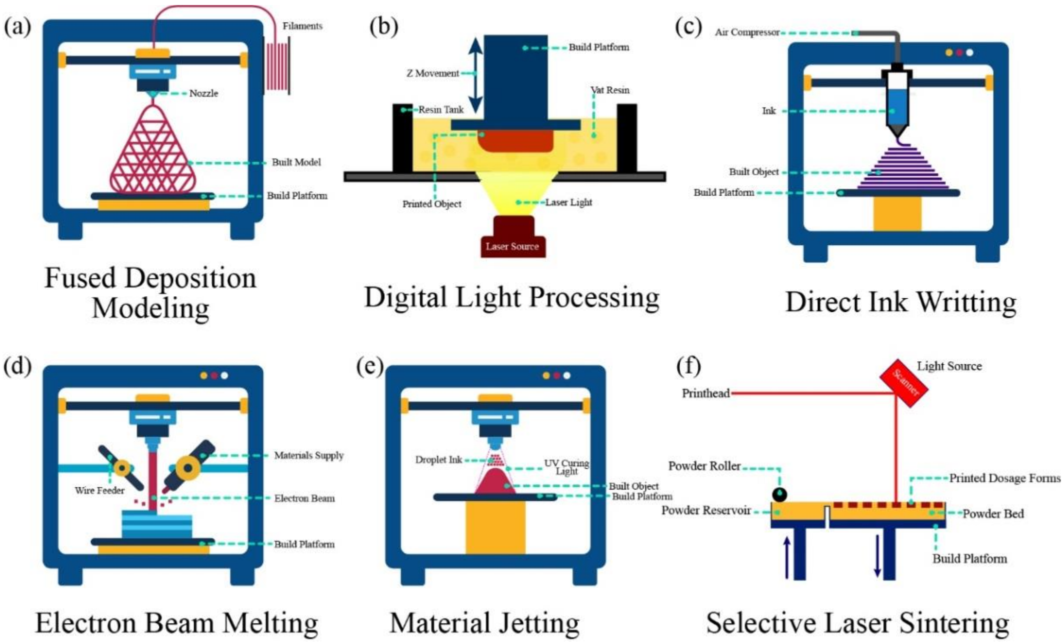

Figure 1. Schematic diagrams of nanomaterials based Additive Manufacturing technologies main methods: (a) Fused Deposition Modeling (FDM), (b) Digital Light Processing (DLP), (c) Direct Ink Writing (DIW), (d) Electron Beam Melting (EBM), (e) Material Jetting (MJ), and (f) Selective Laser Sintering (SLS).

3. Classification of nanomaterials

The classification of nanomaterials is based on dimensionality, as shown in Figure 2.

According to Siegel, nanostructured materials are classified into: zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanomaterials.

Zero-dimensional nanomaterials: all dimensions (x, y, z) are Nanoscale, i.e, a size not larger than 100 nanometers. This includes nanospheres and nanoclusters. One-dimensional nanomaterials: In the present instance, two dimensions (x, y) are on the nanoscale, and one is not. Nanowires, nanorods, nanotubes, and nanofibers fall under this category. Two-dimensional nanomaterials: where one dimension (x) is at the nanoscale and the other two are outside the nanoscale. Two-dimensional nanomaterials are plate-like. This includes nanometer-thick nanofilms, nanolayers and nanocoatings. Three-dimensional nanomaterials: These materials are nanoscale and aren't limited to any particular dimension. Three arbitrary dimensions that are greater than 100 nm exist in these materials. Multiple arrays of nanometer-sized crystals in various orientations comprise bulk (3D) nanomaterials. These consist of 0D, 1D, and 2D structural components near one another to produce interfaces, dispersions of nanoparticles, bundles of nanowires and nanotubes, numerous polycrystalline nanolayers, and bundles of 0D, 1D, and 2D structural elements. [13-16].

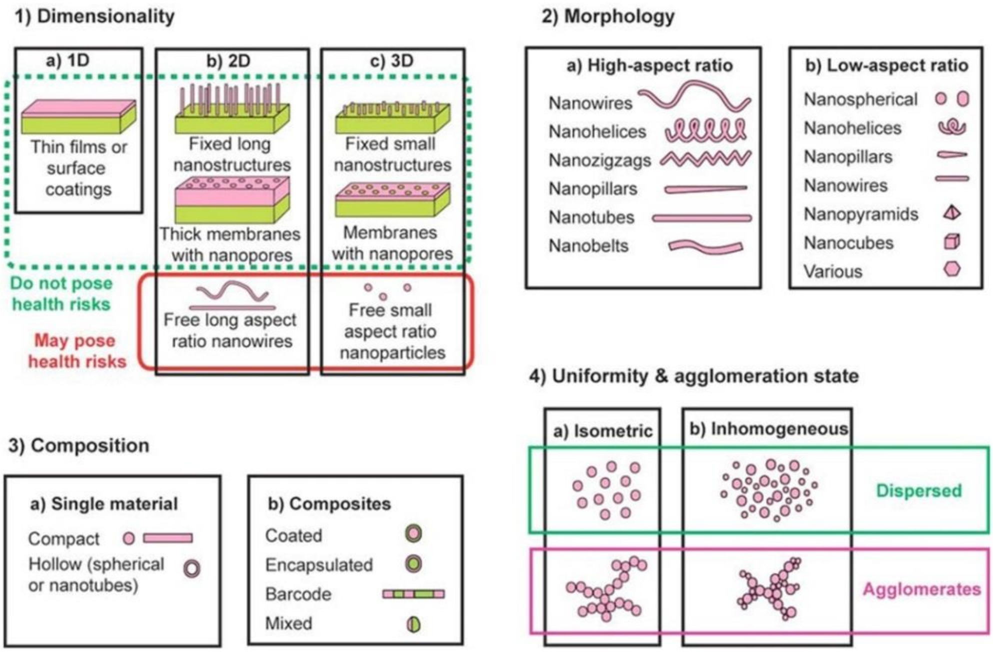

Figure 2. Classification of nanostructured materials based on the size, shape, content, uniformity, and aggregation condition of the structures. [16].

For clarity, we again divide nanomaterials into four categories: **Figure 3** displays several nanomaterial varieties. Materials based on carbon, metal, dendrimers, and composites are listed in order from first to fourth.

Carbon-based materials: These carbon-based substances are hollow spheres, ellipses, or tubes. The cylindrical ones are known as nanotubes, while the spherical and elliptical ones are known as fullerenes. **Metal-based materials:** Quantum dots, which range in size from a few nanometers to hundreds of nanometers, are tightly packed semiconductor crystals made of hundreds or thousands of atoms. Nano-gold, nano-silver, titanium dioxide, and other metal oxides are also included. **Dendrimers:** Dendrimers are molecules that repeat branching. The word "dendron" (tree) is Greek in origin. These nanomaterials are branch-containing nanoscale polymers. Numerous chain endings on the dendrimer surface can carry out particular chemical operations. Dendrimers for photoelectrochemistry, molecular identification, and nanosensing technology. They might help with drug delivery. **Composite:** A composite is created by mixing one type of nanoparticle with another or with more extensive bulk materials. Nanoscale clay-like nanoparticles are added to materials (such as packaging and automotive parts) to improve products' mechanical, thermal, and flame-retardant qualities. [17]

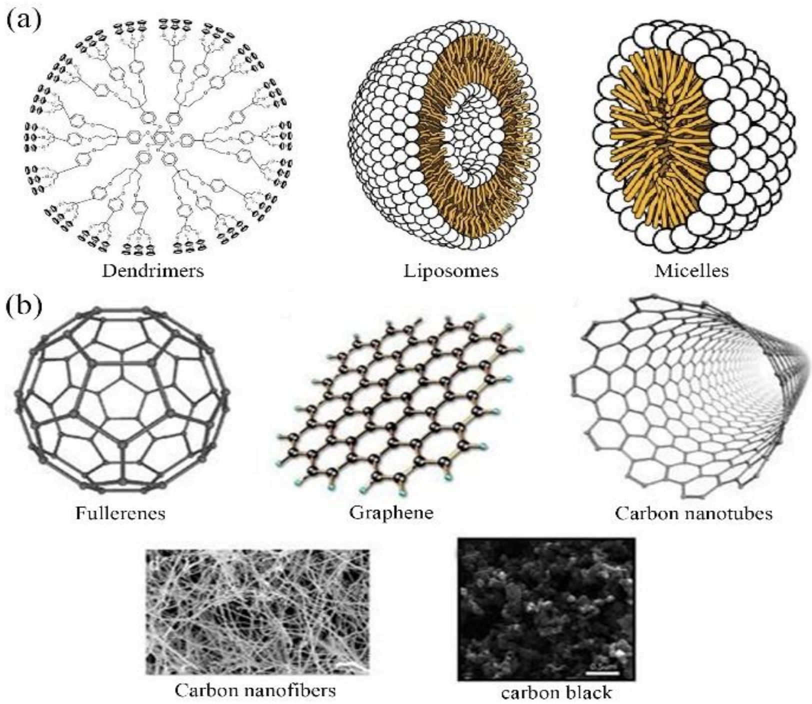

Figure 3. Some types of (a) Organic nanoparticles, and (b) Carbon based nanoparticles. [17].

A.K. Heim et al. [18] isolated graphene in 2004 at the University of Manchester. For their innovative work, they were awarded the 2010 Nobel Prize. A crystalline form of carbon called graphene has a hexagonal pattern on an atomic scale in two dimensions. One carbon atom in this structure forms four bonds: three s-bonds (sp^2 hybridization) next to each other and one out-of-plane p-bond. As the fundamental structural component of other allotropes, including graphite, fullerenes, nanotubes, and nanocones, it is called the matrix of all carbon nanomaterials **(Figure 3)**. FULLERENE Harold Kroto, Richard Smalley, and Robert Curl [19] found the first fullerenes in 1985 by using a laser to vaporize graphite rods in a helium atmosphere. Graphene sheets are rolled into tubes or spheres to form fullerenes, an allotrope of carbon. It is a cage-like molecule with 20 hexagonal hollow spheres joined by single and double bonds between 60 carbon atoms (C60). Twelve pentagonal faces with a football-like pattern. In honor of American architect and geodesic dome pioneer Buckminster Fuller, they are also known as Buckyballs. The fullerene (C60) structure is depicted in **Figure 3**. Lijima Sumio of Japan discovered carbon nanotubes in 1991, which are extended varieties of fullerenes [20]. The diameters of carbon nanotubes, which are tubular materials made of carbon, range from 1 nm to 50 nm. Carbon nanotubes (CNTs) are cylindrical structures of one or more graphene (lattice) layers. Carbon nanotubes display a distinct combination of stiffness, strength, and toughness compared to other fiber materials. Thermal and electrical conductivity are also comparatively high compared to other conductive materials. The following categories can be used to categorize carbon nanotubes: Single-walled nanotubes

(SWNTs): Depending on how the graphene sheet is coiled, these can be chiral, armchair, or zigzag. Multi-Walled Nanotubes (MWNTs): Consisting of multiple single-walled nanotubes. Nanotubes of different diameters. Multi-walled nanotubes are shown in **Figure 3**. [21]

These are defined as structures with nanometer-scale diameters and unconstrained lengths. Nanowires are significantly longer than their diameter, in other words. They are also known as quantum wires due to the various quantum mechanical effects they exhibit at this size. Nanowires come in a variety of varieties. Examples include metal nanowires, carbon nanowires, and molecular nanowires. Conical carbon structures called carbon nanocones have at least one dimension: one micron or less. These are made from graphene sheets that have been wrapped. Nanocones are distinct from nanowires in that their height and base diameter are the same. The cone's aperture angle (vertex) is not chosen at random, as shown by the electron microscope, with optimal values around 20°, 40°, and 60°. Ekimov [22] first discovered quantum dots (QDs) in a glass matrix. These are semiconductor nanoparticles with a diameter of 10-100 atoms. The properties of quantum dots depend on their shape and size. They aren't all the same. Despite their adaptability, the centers of quantum dots contain harmful substances. Hazardous heavy metals seeping from their colloidal forms may be what causes QDs to be dangerous. Additionally, the fundamental qualities of QD size and surface chemistry may be toxic. These materials may pose a potential risk to human health, yet their use is increasing rapidly. It consists of many nanoparticles with a restricted size distribution and at least one dimension between 1 and 10 nm. Generally put, it is a fine aggregate of atoms and molecules. Nanoclusters contain hundreds of atoms, while larger aggregates (called nanoparticles) can contain over 1,000 atoms. The term "magic number" refers to the stability of a sizeable critical cluster's atomic composition. Nanoclusters provide a bridge between bulk materials and atomic or molecular structures. Although a specific sample may have dimensions more than 100 nm along the x, y, and z axes, nanosponges can be categorized as nanomaterials due to a network of nanometer-sized cavities within the volume. From this perspective, nanosponges have nanostructural features, but are not usually nanoparticles. The material's nanometer-sized particles are responsible for the stunning color change. Although gold is typically generated with a dazzling yellow color, it is invariably red when created at the nanoscale. In other words, the size of the gold particle affects the color of the gold. The so-called Lycurgus Cup **Figure 4**, now conserved in the British Museum in London, provides an astounding illustration of this phenomenon.

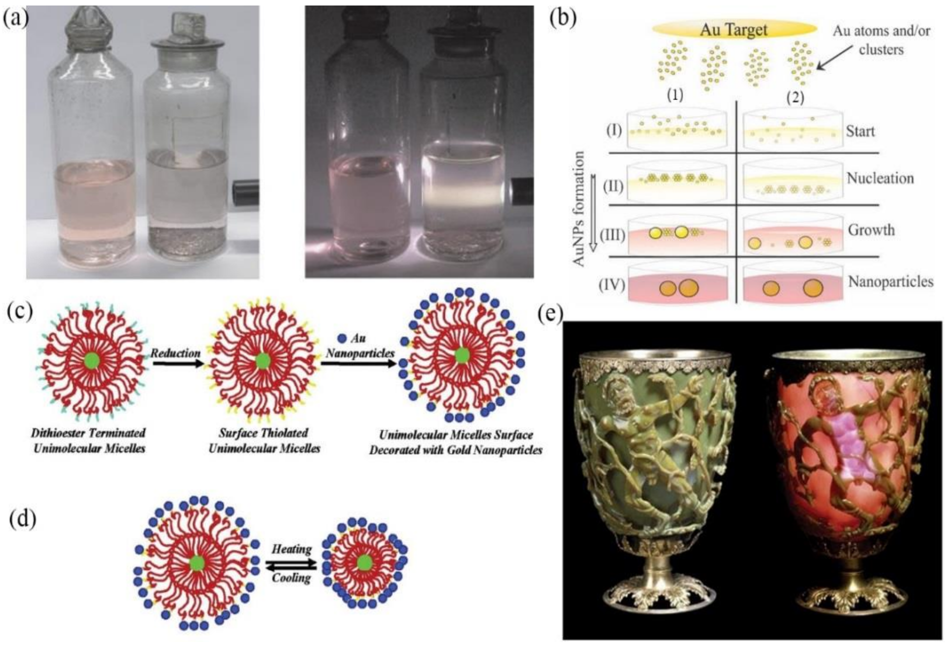

Figure 4. (a) Gold in the Colloidal nanoparticles is in reducing the aqueous solution of $HAuCl_4$. And its optical properties, (b) AuNPs are sputtered onto castor oil using two different strategies for nucleation and growth, where (1) nucleation begins at the oil/vacuum interface and (2) nucleation begins in the bulk liquid phase, (c) A schematic illustration of the two-step process used to prepare the hybrid unimolecular micelle surface decorated with gold nanoparticles and (d) the thermo-tunable spatial distance between the gold nanoparticles attached at the unimolecular micelle surface, and (e) transmitted light images of the King Lycurgus Cup at the British Museum in London. [23]

3.1 Chemical Synthesis Methods

The chemistry of nanoparticle production is inherently simple, and nanoparticles can often be synthesized in large quantities. In addition, during the chemical synthesis of nanoparticles, particle size can also be controlled at the nanoscale. There are many ways to make nanoparticles chemically, such as reduction, co-precipitation, nucleation, sol-gel, flow injection, electrochemical, solvothermal, hydrothermal, and microwave-assisted techniques. [24].

3.2 **Polymerization**

This technique is widely used to create nanomaterials. Due to its significance in numerous technical domains of application, the creation of microemulsions during polymerization has been the subject of intensive investigation worldwide. Applications for enzyme catalysis, reactions of organic and bioorganic nanoparticles and nanocapsules, chemical synthesis, cosmetics, medicines, agriculture, metal cutting, lubrication, and food are among them. [25]

3.3 UV-initiated photoreduction

Citrate, polyvinylpyrrolidone, polyacrylic acid, and collagen are protected and stabilized nanoparticles made at room temperature with UV light. Nanorod and dendrite synthesis and growth mainly depend on the levels of silver nitrates and polyvinyl alcohol. [26].

3.4 Characterization of nanomaterials

The size, stability, and existence of metallic signals in synthesized nanomaterials are being determined and identified using several advanced techniques that are still being developed (Table 1). There are two primary approaches for characterizing nanomaterials: microscopes and spectroscopy.

Table 1. Nanoparticle fabricating with actinomycetes.

Actinomycetes	Type of nanoparticle	Morphology	Size range (nm)	Location/ Organelle
Alkalotolerant actinomycete (Rhodococcus sp.) [27]	Gold	Spherical	5-15	Intracelluar
Streptomyces viridogens strain [HM10] [28]	Gold	Spherical and rod shaped	18-20	Intracellular
S. albidoflavus [29]	Silve	Spherical	14.5	Extracellular and Intracellular
Nocardiopsis sp. [30]	Gold	Spherical	7-15	Extracellular

4. Nano composite materials in additive manufacturing

Multi-walled carbon nanotubes (MWCNTs) distributed in ABS resin enhance material characteristics and the usage of nanotechnology in additive manufacturing (AM) compared to ordinary ABS filaments. Composites offer the potential for a process. The use of nanocomposites in AM facilitates the production of complex structures that cannot be produced by traditional manufacturing methods, enabling superior material properties and optimizing part weight, shape and strength. Reducing sintering temperatures, increasing density, decreasing shrinkage and strain, and increasing electrical conductivity are all benefits of metal nanoparticles. Increased tensile and fracture stresses, more brittle parts, rougher final surfaces, lower densities, significantly improved thermal and electrical conductivity, and faster cell proliferation rates are all characteristics of carbon nanomaterials. Ceramic and semiconducting nanomaterials with improved sintering qualities (aluminum oxide), more rigid but less brittle components (silicon dioxide), and greater tensile strength and modulus [31]. Nanomaterial aggregation in print media is one difficulty with employing nanomaterials in additive manufacturing (AM) processes. This can be overcome by adequately functionalizing the nanoparticles with organic linker molecules. Nanomaterials impact the depth of stereolithography, and potential remedies include Finding a UV light source or material appropriate for a specific wavelength. You can avoid nozzle clogging by identifying the ideal composition for free-flowing nanomaterials at high concentrations, nozzle. In circumstances where nanomaterials are not employed in laser sintering, one potential solution is the fabrication of core-shell structures. Final components printed using nanomaterials have more significant porosity than printed parts in those cases. The shell is a printed substance that improves the density of the finished item, while the center is a nanomaterial. Research on nanocomposite reinforcements of SL resins has also achieved gratifying results. To improve the mechanical properties of epoxy-based resins, support and embed layers of nonwoven glass fibers in hardened pieces. This increases the tensile strength. [32-35]

An atomic-scale honeycomb lattice of ice composed of carbon atoms is known as graphene. Graphene has emerged as one of the most promising nanomaterials due to its unique mix of properties. This paves the way for their employment in various applications, including sensors, biological devices, optics, and electronics. For instance, nanomaterials based on graphene have numerous applications. It is anticipated that they will be used in energy-related domains. A few examples on this are: rechargeable batteries' energy capacity and charging rate are enhanced using graphene. Super energy storage capacitors are made from active graphene; graphene electrodes are a potential method for making affordable, lightweight, and flexible solar cells. Graphene mats with multiple uses are potential substrates for catalytic systems. High-power-density capacitors can be used in various electric vehicles and powertrain applications. The creation of lightweight and compact high-energy-density capacitors is the field's bottleneck. To improve the energy density of dielectrics, methods including directed filler dispersion have been employed. This research involved the 3D printing of $BaTiO_3$ nanowires, a high-performance flexible poly (vinylidene fluoride-chlorotrifluoroethylene) (P(VDF-CTFE)) nanocomposite

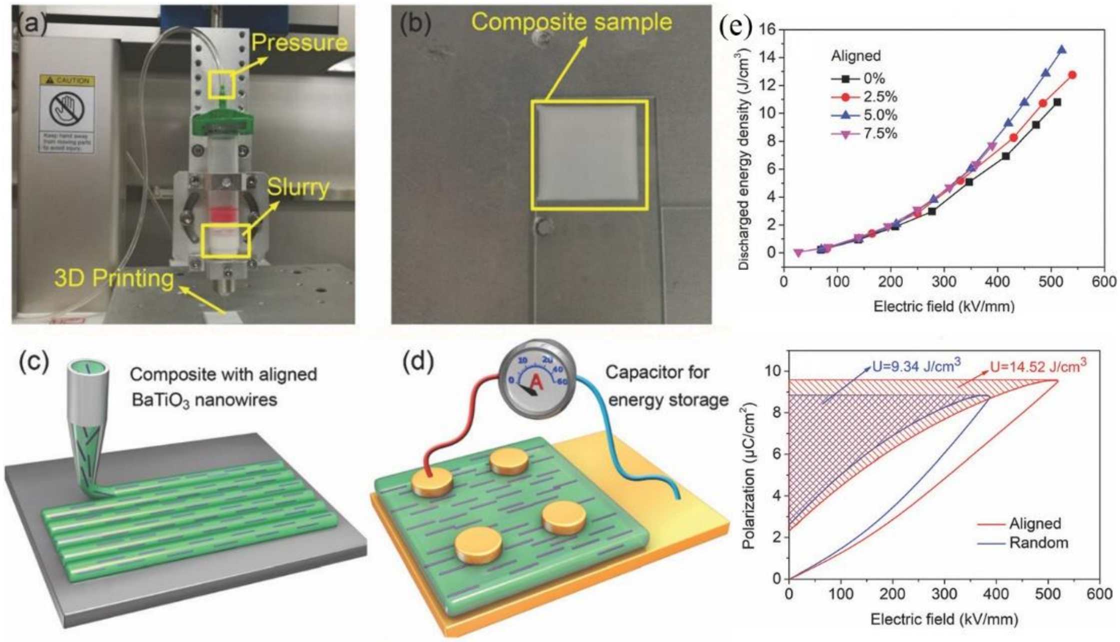

Figure 5. Alignment of $BaTiO_3$ nanowires in nanocomposites: schematic representations of (a-c) the alignment of $BaTiO_3$ nanowires in the P(VDF-CTFE) matrix and (d) a nanocomposite capacitor for energy storage applications Photographs of the printing assembly and a printed nanocomposite sample, and (e) Discharge energy density of P(VDF-CTFE) nanocomposites filled with aligned $BaTiO_3$ nanowires was also examined and maximum discharged energy density and P-E loops of P(VDF-CTFE) nanocomposites with 5.0 vol% aligned and randomly dispersed $BaTiO_3$ nanowires were compared. [36].

Jong Sang et al. [37] use a predictive model to examine the deposition behavior of nanoparticles while looking at the emission of nanoparticles and hazardous air pollutants (HAPs) from 3D printer operations. At the Inha University 3D Printing Center, samples of HAP and five different fused filament fabrication (FFF) types of nanoparticles were taken to a 3-D printer. The number of nanoparticles has a bimodal size distribution, with peaks in both the large (70–100 nm) and tiny (10–20 nm) size ranges. The concentration of 10nm particles rose with the 3D printer operation, reaching a final value of 3.6 times that of the background. Focus Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were used to examine the production and aggregation of nanoparticles. According to model simulations (generations: 16–22), 10–30 nm-sized nanoparticles were deposited in the human lower respiratory tract. There were 14 HAPs found, with benzene, acrylonitrile, and hexane having the most significant amounts.

Maling Gou, Shaochen Chen, and others designed a bionic 3D detoxification device [38]. They prepared a hydrogel with a 3D structure through 3D printing technology and printed polydiacetylene (PDA) nanoparticles with a detoxification function. In the hydrogel matrix, a biomimetic 3D detoxification device is prepared. Nanoparticles can sense and attract toxins, and a 3D hydrogel matrix with a microstructure similar to liver lobules can effectively trap toxins, as shown in Figure 1a. First, colorless PCDA (10, 12-pentacosadiynoic acid) nanoparticles self-assemble into blue and colorless PDA nanoparticles with pore structure by ultraviolet irradiation. Due to the interaction between PDA and toxins, PDA can act to attract, capture and neutralize toxins. Then, the biomimetic 3D detoxification device was prepared by dynamic stereolithography (DOPsL) technology. Figure 1b shows a schematic diagram of the process, using modeling software to design different patterns, which are then transferred to precisely controlled digital mirrors to generate virtual microtasks. The resulting image is projected onto a photocurable resin, which solidifies in the light-projected area, and a patterned layer can be fabricated with only one exposure. This technology has high resolution and fast prototyping. For this experiment, PEGDA (20 wt.%) containing 1% lithium phenyl-2,4,6-trimethylbenzoylphosphinate in H_2O Mix with PDA particle suspension (5 mg ml^{-1}) in equal volume. The mixture is then photopolymerized by DOPsL technology.

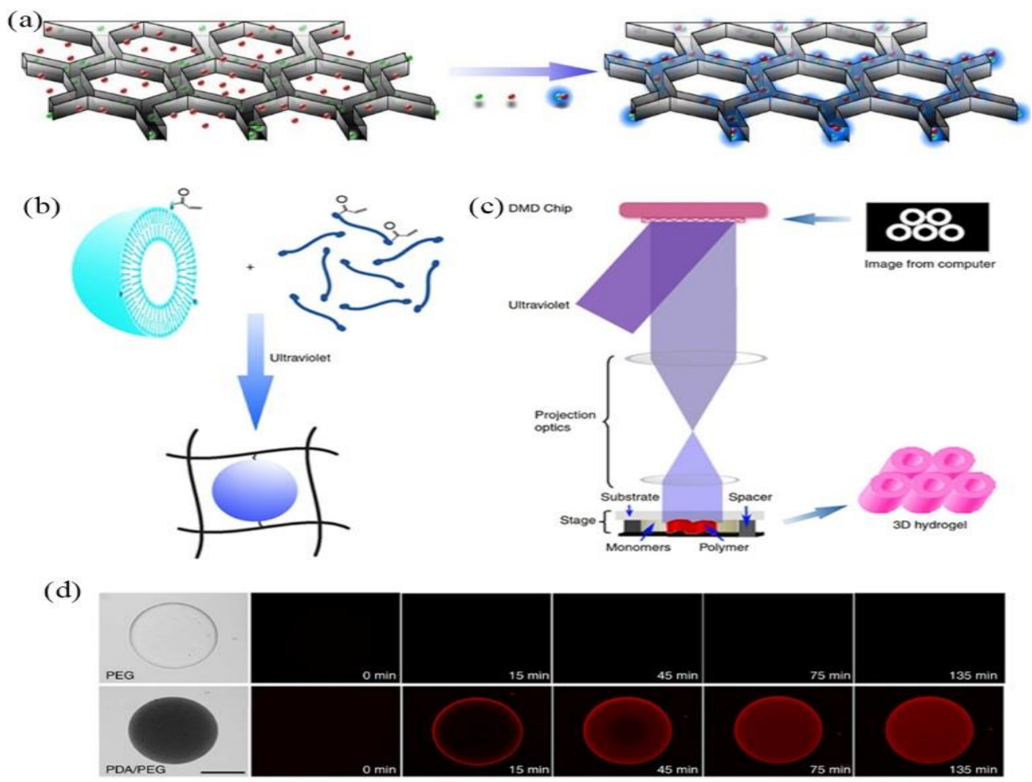

Figure 6. (a) A schematic of 3D technology for detoxification inspired by nature. PEGDA hydrogel matrix (grey) with a 3D liver-inspired structure is fitted with PDA nanoparticles (green). Toxins (red) are attracted to, captured by, and sensed by the nanoparticles, and are effectively trapped by the 3D matrix's modified liver lobule structure, (b) PDA nanoparticles are immobilized in a 3D PEGDA hydrogel. Diagrammatic illustration of the PDA nanoparticle installation within the PEGDA hydrogel network. PEGDA monomer and acrylamide-modified PDA nanoparticles can be photocrosslinked by addition polymerization to bind PDA nanoparticles chemically to the network of PEGDA hydrogel, (c) A schematic illustration showing how to create 3D-structured PEGDA hydrogel using the DOPsL approach. PEGDA hydrogel with a precise 3D structure can be made by carefully planning the masks, and (d) The cylindrical PEGDA hydrogel's fluorescence after being incubated with a melittin solution, either with or without PDA nanoparticles. [39].

4.1 Templating against existing nanostructures

It is simple to create nanowires and other forms of 1D nanostructures from various materials using easily accessible nanowires as templates (physical or chemical). Direct homogenous sample synthesis is challenging (or impossible) for several of these materials. One method involves directly coating these nanowires' surfaces with conformal sheaths made of various materials to create coaxial nanocables. For instance, to create nanostructures that resemble cables, Murphy et al. [40] immediately coated gold nanorods with polystyrene or silica (5–10 nanometers thick). Silva et al. [41] deposited oppositely charged species layer-by-layer (LBL) on nickel nanorods to create nano cables and composite nanotubes.

Coaxial nanowires with a conductive core (made of metal) and an insulating sheath (in the form of amorphous silica or other dielectric materials) have also been created using sol-gel coating techniques. The sheath thickness can be adjusted between 2 and 100 nm by adjusting the precursor concentration or deposition time. Silica nanotubes with consistent wall structure and adjustable size are produced by selectively removing the silver core (by etching with an ammonia solution). As previously indicated, these coaxial nano cables may be the perfect building blocks for the Langmuir-Blodgett self-assembly process that produces 2D and 3D periodic structures. [42]

4.2 All solid materials suitable for generic methods

When a solid has a highly anisotropic crystal structure, growing nanowires in an isotropic medium is not too difficult. As has been shown, it is easy to turn anisotropic materials like trigonal chalcogenides into uniform nanowires with lengths of hundreds of micrometers. This can happen in either the gas phase or the solution phase. Symmetry is broken during the nucleation step in many minerals with isotropic crystal structures. For example, almost all metals form in a face-centered cubic (fcc) lattice, which can lead to anisotropic growth. To achieve this, various techniques have been investigated to decrease the seed's symmetry (or the surroundings of the source) and create nanostructures with a 1D shape. A template-oriented approach to definition offers several valuable illustrations. Another complex strategy uses vapor-liquid-solid (VLS) processes, introducing flat solid-liquid surfaces to disrupt symmetry. Many gas-phase and solvothermal methods have shown that it is possible to successfully induce and maintain 1D growth by controlling the system's supersaturation below a specific threshold. Anisotropic growth has also been investigated using capping chemicals to modulate the growth rate of various solid planes kinetically. [43]

Nanowire growth from the vapor phase: Gas phase synthesis is creating 1D nanostructures like whiskers, nanorods, and nanowires that have received the most research. Keeping supersaturation at a manageable level can turn any solid material into one-dimensional nanostructures [44]. **Vapor Liquid Solid Methods:** The VLS process is the most successful way to make single-crystal structured nanowires using steam. Wagner and his colleagues devised the process in the 1960s to make micron-sized whiskers. Lieber, Yang, and many other research groups have shown that it can be used to make a wide range of inorganic whiskers. The material was repurposed to produce nanowires and nanorods. In a typical VLS process, gaseous reactants break up into nanometer-sized catalytic metal droplets that start, grow, and grow wires from single crystal rods [45]. **Liquid hydro methods for solutions:** Buhro and his colleagues developed a solution-liquid-solid (SLS) approach for producing highly crystalline III-V semiconductor nanowires at low temperatures based on the process' resemblance to the VLS process. Low melting point metals like In, Sn, and Bi are frequently used as catalysts in procedures to break down organometallic precursors into the final product. Essentially, the end products are single-crystal whiskers or filaments with lateral dimensions of 10–15 nm and lengths of up to several microns [46]. **Solvo thermal Methods:** Solvothermal synthesis uses solvents at pressures and temperatures above the critical point to increase solubility and speed up the interactions between solids [47]. **Capping reagents-based solution phase methods:** The specific surface energy connected to a crystal's facets governs its form. According to Wolff's facet theorem, the faces around an equilibrium crystal should have the least total surface energy [48].

In the past, molten metal catalysts were used to make nanowires from different 3D crystalline semiconductors through vapor-liquid-solid (VLS) growth. With their anisotropic structures and properties, 2D/layered semiconductors create more opportunities for material design when shaped into 1D nanostructures. Compared with hexagonal 2D crystals like graphene, hexagonal boron nitride, and transition metal dichalcogenides, which tend to roll into nanotubes, VLS growth of layered III and IV monochalcogenides produces different nanowires and nanoribbon morphologies, which crystallize in bulk With nanoscale footprints and layered structures exceeding tens of micrometers in length. One-dimensional van der Waals (vdW) architectures can be used to make different shapes. Peter et al. [49] discussed about controlling critical structural features and the new functions that can be used. The authors' discoveries show that these materials are a particular type of nanostructure because they can do much more than extend 3D crystalline VLS nanowires to vdW crystals.

4.3 Methods for measuring nanoparticle size:

Scanning electron microscopy SEM: Direct perception of morphology is provided by scanning electron microscopy. They supply bound data on size variance as well as actual population normal. This technique is cumbersome and expensive and often requires mutual knowledge of variance estimates. **TEM** is mostly utilized to demonstrate the morphology of nanoparticles. **Atomic force microscopy:** determination of Surface Topography and Roughness Distribution of Nanoparticles Using 2D and 3D AFM Images. **Zeta potential: u**sed to determine the zeta potential value, size, and surface charge of nanoparticles. **Surface hydrophobicity:** Measured by multiple techniques including hydrophobic interaction chromatography, biphasic partitioning, and probe adsorption. **Drug release assays**, like drug loading assays, are also classified as studies of drug release mechanisms. [50-52].

5 Characterization

5.1 Thermal stability

Since hard coatings' mechanical and tribological qualities deteriorate when employed at high temperatures, it is crucial to assess their thermal stability. During operation, the cutting tip's temperature can rise to 1000 °C. Finding coatings that can function at these high temperatures is more important due to environmental concerns that restrict the usage of lubricants and coolants. Coatings can be categorized into three groups based on their hardness: super hard coating with H > 80 GPa and carbide with H > 40 GPa. A hard coat is beneficial for two main reasons. Nanoscale structures or high-pressure stress. High biaxial compressive stress is used as the recovery's primary force. The compressive stress increases as the thermal activation energy required to begin recovery decreases. The coating will become more ultra-hard but less thermally stable under high biaxial compressive stress. Dislocations boost the coating's microscopic compressive stress, which speeds up healing. The small grain size of nanoscale coatings limits grain development and boundary slip, enhancing thermal stability. [53-54]

5.2 Mechanical properties

Synthesizing gradient nanostructured materials like nanoparticles, nanolaminates, nanotwinned metals, and alloys opens up new ways to learn how mechanical behavior changes with gradients. Many of the mechanical properties of these newly graded materials are unique, like strength-ductility synergies, exceptional strain hardening, better fracture and fatigue resistance, and outstanding wear and corrosion resistance. The hardness of amorphous metal multilayer films was investigated by the nanoindentation method. Amorphous CuNb, FeB, and FeTi bilayer material systems were grown on sapphire substrates by DC sputtering with a total thickness of 1 μm. The bilayer period (Λ) ranges from 2 to 50 nm. X-ray diffraction (XRD) and electron diffraction were used to prove that the films were not crystalline. The layer structure was verified by transmission electron microscopy and grazing-angle XRD. By measuring the hardness and elastic modulus of the films with nanoindentation, it was shown that they were statistically the same as what would be expected for normal mixtures. [55]

In contrast, the hardness of crystalline multilayers usually gets better as the bilayer period gets smaller than 10 nm. Since the hardness of the amorphous films didn't change much, this is a strong sign that dislocation-mediated mechanisms can't control the uneven flow of amorphous metals. The mechanical properties of nanostructured materials, defined as having an average grain size of 50-200 nm, are reviewed, and the underlying mechanisms are discussed. His main focus is on nanostructured materials that combine nanocrystalline powders and put an electric charge on them. This review shows that the history of treatment has a big effect on how machines work, as shown by the following observations:

- Low-strain hardening behavior is often seen during the plastic deformation of nanostructured materials that have been milled (also called mechanical milling or polishing). This effect could be caused by dislocation annihilation or dynamic recovery during plastic deformation.
- The presence of porosity or bimodal phase distribution can rationalize the reported asymmetry of yield strength between tension and compression.
- Pronounced strain hardening behavior is often observed in electrodeposited nanostructured materials. The observation of strain hardening in nanostructured materials can be explained based on dislocation propagation.
- The often-reported low ductility of nanostructured materials is related to the lack of dislocation activity.

A recent review suggests that this problem can be solved using multiple-length scales in microstructures. Nanoscale metals have special properties, so it is necessary to develop a process for fabricating 3D metal structures with macroscopic overall size and microscopic submicron. Current wire- and filament-based processes such as plasma deposition and electron beam freeform fabrication can produce millimeter-sized devices, and powder-based processes such as selective laser melting (SLM) and laser-engineered mesh forming can limit the minimum feature size At around 20μm, local electroplating or metal ion reduction methods can very slowly fabricate structures with a resolution of less than 500 nm. Electrochemical fabrication (EFAB) allows the fabrication of structures with a resolution of 10 μm, but is limited to a layer thickness of 4 μm and a total height of 25-50 layer structure [56].

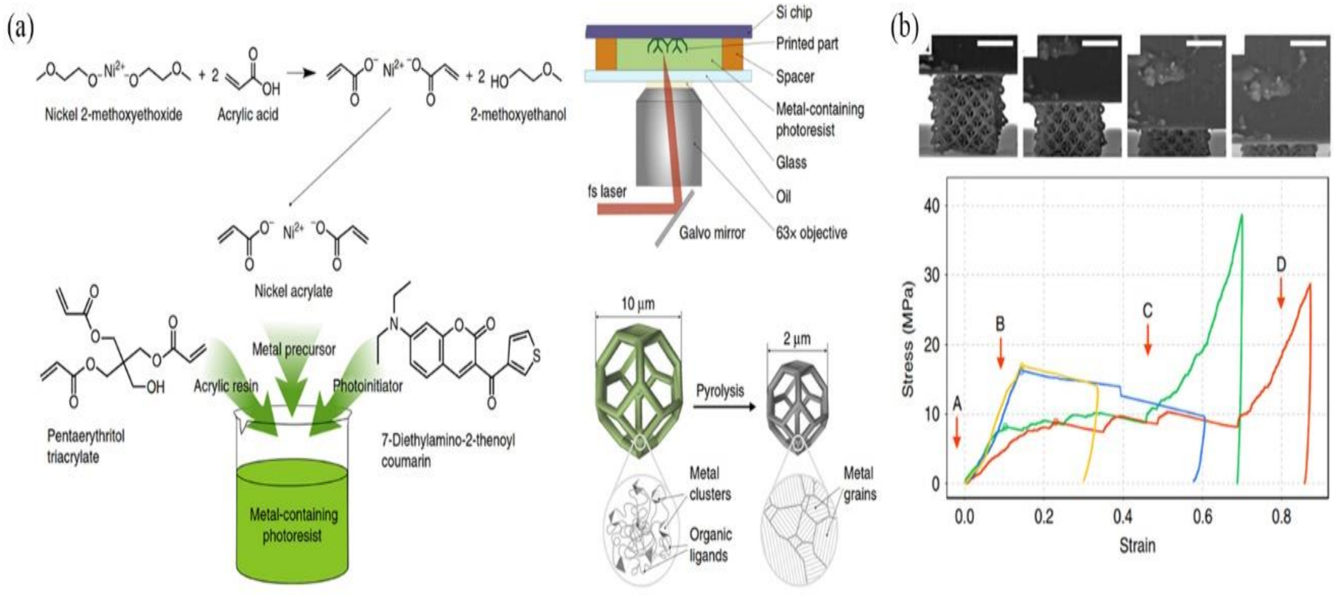

Figure 7. (a) Metal additive manufacturing at the nanoscale Metal precursors with cross-linking properties are created using the ligand exchange process. A transparent metal-containing photoresist is created by combining metal precursor, acrylic resin, and photoinitiator. Schematic of the scaffolding's two-photon lithography (TPL) method. A metal-containing polymer part's manufacture is shown schematically. The polymer was epyrolized to remove the organic content and turn it into a metal, and (b) Nickel octet nanolattices that were 3D printed were compressed in situ uniaxially. Data on stress and strain for four nickel nanolattices compressed [56].

5.3 Electron transport properties

A hybrid device was developed with a ZnO nanowire array and poly (3-hexylthiophene). Using ultraviolet (UV) light at 350 nm, we examined the optoelectronic characteristics of ZnO NW arrays and hybrid structures. In this manner, P3HT is prevented from being activated, and the actual electron-transporting capacity of ZnO nanowires is discovered. According to our findings, the hybrid structure had faster optoelectronic responses than the ZnO NW array, which took 9 s. Additionally, a sluggish photoelectric reaction connected to the surface state was seen. Discussions are made regarding the charge transfer process and the surface state's impact. Our recent research sheds light on the ZnO NWs arrays used in hybrid polymer solar cells' electron transport properties. For maximizing gadget performance, this is crucial. Due to its exceptional electrical properties, graphene, a two-dimensional, single-layer structure, has generated a lot of study attention. For instance, at ambient temperature, graphene's electron mobility can reach 106 cm^2/Vs, around 70 times more than silicon's. Due to its high electron mobility and compatibility with other materials, graphene makes a viable choice for high-frequency analog circuits. [57]

Graphene nanoribbons (GNRs), which can end in an armchair or zigzag edges, can be created by cutting pure graphene monolayers into long, thin strips. GNRs can be metallic or semiconducting depending on the edge's type and width. The edge magnetism and edge state stability of graphene nanoribbons have recently been discussed, and it has been hypothesized that the inherent appeal of GNRs may be unstable at ambient temperature. The carbon sp^2 hybridization network can describe the honeycomb lattice of graphene. Ideal 2D graphene is a zero-gap semiconductor with electronic valence bands connected to and * bands emanating from p_z orbitals intersecting Dirac points in reciprocal space. It is a single-atom-thick layer. The key to preparing these novel aerogels is to prepare extrudable graphene oxide-based composite inks and to design the 3D printing process to adapt to the processing technology of aerogels. The research group utilized extrusion-based 3D printing technology, direct-ink writing (DIW), to fabricate highly compressible graphite air gel microlattices. DIW technology uses a three-axis kinematic mechanism to assemble three-dimensional structures from extruded continuous "ink" filaments at room temperature. The manufacturing process scheme of 3D-GCAS is shown in **Figure 8**. The composite ink mixed GO suspension (40 mg cm^{-3}), GNP and silica fillers, and catalyst (R–F solution with sodium carbonate) to form a uniform high-viscosity ink. The composite ink is then loaded into a syringe tube, and the 3D structure is extruded through a micro-nozzle. Finally, the print can be processed into aerogels through gelation, supercritical drying, and carbonization methods, followed by silicon dioxide etching with hydrofluoric acid.

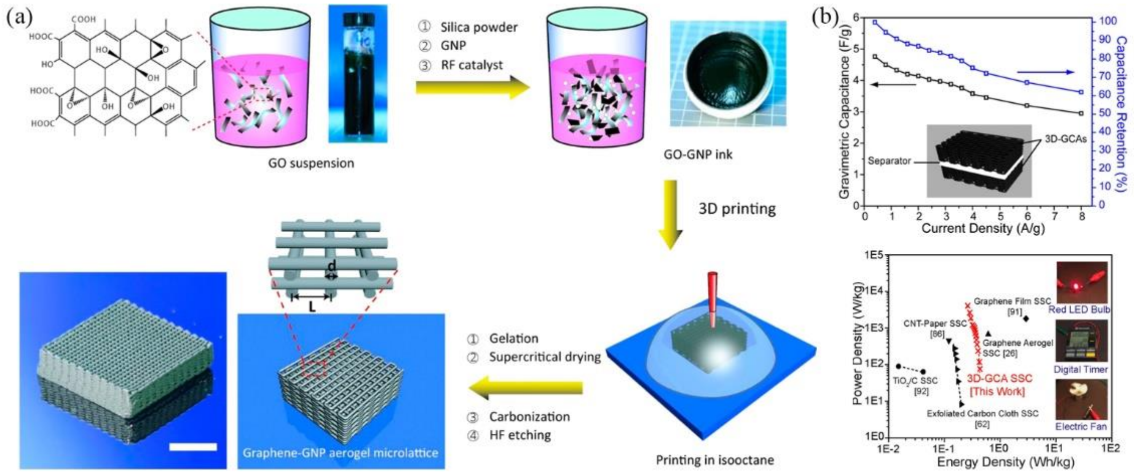

Figure 8. Illustration of the fabrication process in a schematic (a) The already-made aqueous GO suspension was supplemented with hydrophilic fumed silica powder, GNPs, and R-F solution. A homogeneous GO ink with intended rheological characteristics was obtained after mixing. For the purpose of preventing structural shrinkage during printing, the GO ink was extruded through a micronozzle in an isooctane bath. The printed lattice was gelled at 85 °C for the entire night before being dried using supercritical CO_2. The building was then heated for three hours to 1050 °C in a nitrogen environment. Finally, using a diluted hydrofluoric acid aqueous solution (5 wt.%), the silica fillers were removed 10 mm is the scale bar, and (b) Estimated as a function of current density are the gravitational capacitance and capacitive retention. Schematic representation of the 3D-GCA SSC in the inset. Comparative Ragone plot of the 3D-GCA SSC with reported values added. [58]

Recently, researchers Li Qingwen and Zhang Yongyi of the Suzhou Institute of Nanotechnology and Nanobionics, Chinese Academy of Sciences, and Professor Yang Zhengpeng of Henan University of Science and Technology proposed a kapok-derived thin-walled, high microporosity, high specific area, rich heteroatom doping, and appropriately curved Using quasi-two-dimensional carbon tiles (CT) as unique skeleton support, a new CT-single-walled carbon nanotube (SWNT)-$NiCo_2O_4$ pseudocapacitive electrode was prepared through an ink 3D printing strategy. In the 3D printed electrode structure, CTs and SWNTs are coupled to form interconnected multi-level holes and continuous conductive networks, achieving uniform and high-quality loading of the active $NiCo_2O_4$, while ensuring unobstructed ion diffusion channels and sufficient electron transmission path. Benefiting from the unique characteristics of the electrode structure, the assembled asymmetric supercapacitor exhibits high specific capacitance and energy density and outstanding long-term cycling stability. Notably, the device still shows excellent electrochemical energy storage performance even when the electrode thickness is increased. The author provided a new strategy for constructing pseudocapacitive electrode structures with high capacity and power density. [59]

On the other hand, graphene-based devices that can be turned on and off, like transistors, can only be made real when semiconductor graphene is available. Since the equivalence of the two carbon sheets in graphene is directly related to the lack of a gap, taking away this equivalence can open the gap and change the electronic properties of graphene. Graphene gaps can be closed in many ways, such as doping the substrate, making the edges functional, or changing the chemical composition. Considerable efforts have been made in recent years to find ways to exploit the electrically tunable bandgap in graphene.

5.4 Optical properties

The optical characteristics of nanocomposites can diverge significantly from those of the component components. To create novel materials with desired optical properties, composite materials are made. This article discusses ideas and models developed to link the morphology of the composite structure and the constituent materials' properties to the linear and nonlinear optical properties of composites. It also reviews experimental research designed to test these theories and models. The specifically covered morphologies include fractal structures, layered structures, and the morphologies of Maxwell Garnett and Bruggeman [60]. The growth, behavior, and development of phototrophs and autotrophs depend on light. Silica-based materials are used by a wide range of diverse species for their internal and exterior architecture. Nanoscale, well-organized silica biomaterials with low refractive indices and extremely low visible absorption coefficients are of particular interest for optical research. The silica materials from glass sponges and diatoms have recently been studied, and they exhibit intriguing optical characteristics such as optical guiding, diffraction, focusing, and photoluminescence. Glass sponge spicules and diatom shells both have features that combine light focusing and guiding.

In a paper published based on the study, the research team noted that the new findings in this study provide key insights and considerations for the development of future nanoparticles/nanomaterials, 3D-printed functionalized "smart" materials. Cole Brubaker, one of the paper's authors and a doctoral student in civil engineering at Vanderbilt University, said the research team embedded gold nanoparticles into polymer printing materials and studied whether they could help mark these defects. The gold nanoparticles used in the study are 100,000 times thinner than human hair, similar to the gold found in gold jewelry, but they have unique optical properties that do not degrade over time. The research team used a new method to mix gold nanoparticles with dissolved plastic polymers, dispersing the gold particles throughout the medium. When the mixed materials dry and harden, the plastic is extruded or pressed into gold nanoparticle-filled polymer filaments or thin tubes, which can be used in standard 3D printers. After 3D printing is completed using this material, the 3D printed parts are put into a unique UV-visible spectrophotometer to check for defects. Taking advantage of the material's absorbance characteristics of gold nanoparticles, the research team only needs to scan the surface of the 3D-printed plastic part. Those locations where the internal absorbance decreases indicate defects in the material at that location. This inspection method that finds defects in 3D printed parts through one-time non-destructive inspection is high-speed, usually only taking a few seconds. 3D Science Valley learned that the research team has proven that 3D printed components can "self-report" existing defects through this method, and the research team is using this "smart" material to expand more possibilities [61].

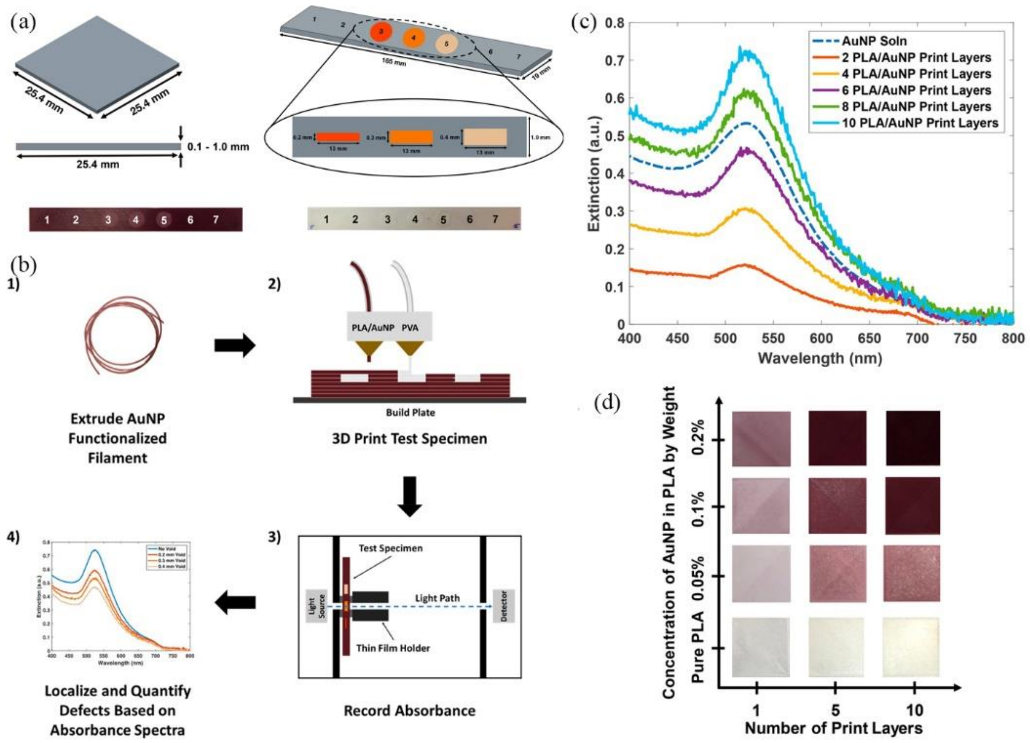

Figure 9. (a) Schematic illustration of solid thin-film samples produced via 3D printing, the average absorbance and error bars provided here were calculated statistically from a total of nine scans that were recorded from three different test samples, and typical PLA/AuNP void-spacing sample made using 3D printing, (b) Thin-film and void space specimens' absorbance responses are measured using a schematic illustration of the sample fabrication/printing and setup utilized for defect identification tests, (c) Absorbance spectra of PLA/AuNP films that were 3D printed with 0.1% AuNP by weight (with an increase in print layers from 2 to 10 total layers) and AuNP suspended in toluene (with an SPR peak at 521 nm), and (d) 3D printed films of PLA instead of PLA/AuNP at 0.05%, 0.1%, and 0.2% AuNP by weight concentrations. [61]

Additionally, most of these intriguing investigations addressed these features in non-aquatic settings using pure biomaterials, first boosting the refractive index contrast inside the structure and subsequently enhancing the spectrum distribution. It is crucial to stress that these findings came from a small number of species, even though there is a lot of evidence that silica biomaterials can display intriguing optical features that could be employed in industry. Biological experiments and field research are required to further understand the physiological and structural functions of silica structures in various marine creatures.

5.5 Lasing in semiconductor nanowires

Unique optical characteristics of semiconductor nanowires include extremely confined light emission, effective wave guiding, and amplification. Since even laser excitation is possible by optical pumping, nanowires have great promise for optoelectronic applications. The finite-difference time-domain approach is typically used to process electromagnetic fields. With the many-body effect shielding the Hartree-Fock approximation, the semiconductor Bloch equations describe semiconductor materials' polarization and occupancy numbers [62]. Use a random driver term to introduce spontaneous emission noise. We use simulations of the dynamics of nanowire lasing, including optical pumping, automatic emission seeding, and lasing mode selection, as an example.

5.6 Nonlinear optical properties

All-optical systems are highly interested in nanostructures because of their potential for quick recovery and improved nonlinear optical properties. Organic materials allow for easy synthesis and design flexibility. It is well-established to explore semiconductor materials for nonlinear optics, particularly low-dimensional structures. Various quantum size effects improve the nonlinear optical properties of nanoscale clusters. The creation of nanocrystalline aggregates using a variety of techniques is encouraged in this chapter. The presentation of theoretical analyses of nanostructured materials follows a quick introduction to nonlinear optics. Metals, semiconductors, and wide-bandgap semiconductors are the three material types used in experimental research of secondary and tertiary processes. While the majority of research has examined individual clusters' characteristics, this chapter suggests that it may be possible to improve the nonlinear optical constants of clusters that interact closely. The coherent effect of many clusters leads to large nonlinear effects. It is well known that nonlinear optics is a powerful tool for studying material properties. This paper investigates the first hyperpolarizability of various molecular objects using two key nonlinear optical techniques, electric field-induced second harmonic generation (EFISH) and harmonic light scattering (HLS) [63]. The authors first show the binding of pi donors in cyclometallated Ir complexes. Several trinuclear organometallic triaryl-1,3,5-triazinane-2,4,6-triones peripherally functionalized by d6-transition metal acetylide complexes were also investigated. This is a much higher hyperpolarizability than that reported for pure organic derivatives. Second, a series of dipolar and octapolar dithiopheneethylene (DTE) ligands with 2, 4, and 6 photochromic dithiopheneethylene units with different metal ions were synthesized to form 2,2-bipyridines. [64]

The ligand has undergone thorough characterization. According to this study, the creation of closed-ring isomers was followed by a considerable rise in hyperpolarizability. This effective improvement results from the -electron system delocalizing and a strong push-pull chromophore forming in the closed form. Third, they developed a bis(phthalocyanine)lanthanide-(III) with lateral ABAB (a phthalocyanine with alternating electron-donating and electron-accepting groups), AB3 (three donors), and A4 (four donors). The authors investigated the NLO properties of bilayer composites. B4 (no donor group) ligand. The author measured the first-order hyperpolarizabilities and revealed the highest-ever second-order hyperpolarizabilities of octapolar molecules. In the second-order nonlinear activity, f electrons in coordinated lanthanide ions are also seen to contribute directly. Finally, radiolysis was used to create gold nanospheres (AuNS) and gold nanorods (AuNR) with various aspect ratios (AR) ranging from 1.7 to 3.2 nm. The fact that AuNRs have higher second harmonic intensities than nanospheres suggests that they depend on AR. Additionally, they combined the chromophore's derivative, 4-dimethylamino-N-methyl-4-stilbentosylate (DAST), with HeAuNR and saw that the NLO properties of HeDAST were improved in the presence of AuNR. There is proof that DAST derivatives' hyperpolarizability has increased by eight times. [65]

5.7 Photoconductivity and optical switching properties

The photoconductivity and photorefractive characteristics of conjugated organic thin films based on polyimide, polyaniline, and pyridine doped with fullerene and nanotubes were investigated. Investigations into liquid crystal mesophases using nano-objects have also been made. Organics that have been nanosensitized have been found to have increased carrier mobility. Using the four-wave mixing technique, the Ramannas diffraction process is used to study cubic nonlinearity and nonlinear refraction at a wavelength of 532 nm. Written in the 90 to 150 mm-1 spatial frequency range are thin holographic gratings. The energy density is set between 0.1 and 0.9 J/cm2. It is discovered that photoconductive and nonlinear optical properties correlate. There are numerous nano- and microelectronic uses for nanostructured materials. Interest in semiconductor nanoparticles (NPs) is high due to their optical and electrical characteristics. Due to the discrete density of states, they have an adjustable bandgap and improved quantum efficiency. Wide bandgap (3.37 eV) and strong exciton binding energy (60 meV) characterize zinc oxide (ZnO). With good UV emission capabilities, excellent stability, and room-temperature emission, it exhibits intriguing new optical and electrical features. [66-67]

5.8 Field emission properties

Using either flexible alumina templates or nanoporous silicon templates with hexagonal close-packed pores of 50 nm width and 500 nm length, two nanoscale field emitter arrays were self-assembled. The first is a gold 'nanopine' array made by an e-beam evaporating a small amount of gold onto a simple alumina substrate. The second is a collection of nickel "nanoblades" made by evaporating a small quantity of nickel onto a nanoporous silicon template. Scanning field emission microscopy was used to measure the field emission characteristics of the two mesoscopic structures, and the results were examined for the emission of the cathode material. This strategy for synthesizing nanoscale field emitters could result in a flexible and affordable method for creating flexible nanoscale cold cathode emitter arrays [68-69]. The authors looked at electron field emission characteristics in nanostructured carbon clusters (or carbon fibers) produced by catalyst-assisted solid phase epitaxy from diamond or diamond-like films. When a diamond-like film is coated with a thin Fe/Co layer (less than 10 nm) and post-annealed at a high enough temperature (above 950 nm), SEM microscopy and Raman spectroscopy demonstrate that a fibrous carbonaceous material (> 950 nm) is produced. The pre-coated Fe/Co layer initiates the phase transition process. With an applied electric field of 21.6 V, the field emission characteristics of the nanostructured carbon formed on the resulting diamond-like film were Je=300 μA/cm^2. Unlike the boron/nitrogen combination, the doped diamond film's field emission characteristic was Je=1080 μA/cm^2. [70]

6 Applications

The new nanomaterials have a more extensive contact area than the conventional micromaterials. Single nanostructures have recently been developed for use in various bioscience research projects, including those involving nanoparticles, nanofibers, and biosensors and those involving medication development, food, environmental monitoring, proteomics, biomarker analysis, and virus detection. Enzyme nanoparticles (SEN), for example, are among the additional nanomaterials. Nanosensors are frequently made using biosignal sensors.

Nanomedicine: Nanoscale carrier systems can be used to deliver drugs in a more targeted and efficient manner. Nanomedicine combines chemical and mechanical properties to help patients and practitioners create drugs that reach target areas faster than traditional injections or tablets. Unlike existing drugs, nanoparticles can cross specific biological barriers in the body. Use smart nanostructures to develop various new technologies such as sensing, imaging, tissue engineering, biofabrication, nanodevices, and nanorobotics to improve healthcare [71]. **Energy:** Solar energy is one of the primary energy sectors where nanotechnology has exceptional potential. In nanoengineered solar cells, smaller particles and materials with various molecular architectures help absorb more energy. The demand for solar energy has increased recently, and there is now a large number of solar enterprises that can use nanotechnology in their goods [72]. **Electronics:** Processing information quickly and at scale is critical in a world dominated by data. Fortunately, nanotechnology can produce the more compact, quick, and potent electronic processors required to handle the demands of big data. NRAM (nanotube-based nonvolatile random access memory) memory chips, developed by nanotechnology business Nantero to replace high-density flash memory chips, employ carbon nanotubes [73]. **Food:** By making food and food packaging more durable and bacteria-resistant, nanotechnology is assisting in the fight against global food waste. Consumers throw away less food, and stores reject it when food is held for extended periods. For instance, clay nanocomposites provide impenetrable barriers for gases like oxygen and carbon dioxide in bottles, cartons, and packaging films. Nanosensors have been designed to detect bacteria and other impurities, such as salmonella, in packaging plants, and these containers are embedded with bacteria-killing silver nanoparticles [74]. **Environment:** Environmentally beneficial applications include heavy metal nanofiltration systems, wastewater treatment using nanobubbles, and ion-based air purification. Additionally, nanocatalysts can reduce pollutants and increase the effectiveness of chemical reactions [75]. **Textile:** Nanotechnology enables the creation of innovative fabrics that are wrinkle- and stain-resistant, as well as stronger, lighter, and longer-lasting materials for sports equipment and motorcycle helmets. [76]

There are many origins of nanomaterials products in the following order: (1) Personal care and cosmetics (2) Paints and coatings (3) Household items (4) Catalysts and lubricants (5) Sports items (6) Textiles (7) Medical and health care items (8) Food and nutritional ingredients (9) Food packaging (10) Agrochemicals (11) Veterinary medicines (12) Construction materials (13) Weapons and explosives (14) Consumer electronics.

Figure 10. Applications of 3D printing nanomaterials in different fields.

7. Advantages of 3D printing technology in nanomaterials

1) **Precision**: 3D printing technology uses computers to transform complex three-dimensional designs into physical models. The fine particles in nanomaterials produce huge effects based on their small size. Integrating 3D printing technology can increase the unique functions of nanomaterials, such as light, electricity, and heat. Starting with precision and detail can effectively shorten the product development cycle.

2) **Diversity**: 3D printing technology has a variety of materials that can meet the complex requirements in the development of nanomaterials, allowing nanomaterials to obtain more unexpected high-performance characteristics such as reflection and catalysis, increasing their added value.

3) **Cyclicity:** The recyclability characteristics of 3D printing technology bring benefits to nanomaterials. It is understood that nanometers have important functions in antibacterial, fresh-keeping, deodorization, etc., and 3D printing technology uses recycling to extend the service life of nanomaterials, increase their use value, and contribute more to social life.

4) **Environmental protection**: The most critical environmental protection performance of 3D printing technology is energy savings, low toxin emissions, and low power consumption. Because 3D printing technology comes from an electric power supply and because of its high precision. Therefore, regarding energy consumption, resources can be optimized to the greatest extent and avoid waste and environmental pollution. In recent years, composite rare earth compounds developed using nanotechnology can purify automobile exhaust through their powder effect. Nanomaterials and 3D printing technology coincide at this point. Integrating the two will further reduce polluting gas emissions, effectively optimize resources, and avoid environmental pollution caused by resource waste. It is easy to see from this that the combination of the two is perfect.

8. Conclusion and outlook

The above are simple examples of preparing multifunctional micro-nano devices through 3D printing. 3D-printed multifunctional complex structures have an essential role in the manufacturing industry, such as components for MEMS, stretchable/flexible microelectronics, sensing devices, micro antennas, and tissue engineering. To realize the full potential of 3D printed multifunctional nanocomposites, simultaneous advances in both materials and technology are still needed. The first is the design of the materials. The primary method to realize the functionality of micro-nano devices lies in how to modify the "ink" of 3D printing. Whether it dramatically affects the mechanical properties of the electrode or not, the study of materials is critical. Another research direction is the research on the 3D printing process that is, controlling the microstructure by controlling the forming parameters and how to design hardware and software to achieve higher resolution printing.

Overall, 3D printing technology has good development prospects, and with the rapid development of 3D printing technology, the application process of nanomaterials will indeed develop faster. However, this technology still needs to improve in the application of nanomaterials, such as the high cost of the 3D printer and imperfect environmental protection. However, we believe that 3D printing technology will eventually overcome these shortcomings. One day, we will see more complete 3D printing technology, bringing more significant economic and social benefits to the application of nanomaterials and even human society.

Declaration of Competing Interest

The authors confirm that they have no known financial or interpersonal conflicts that would have appeared to impact the research presented in this study.

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