# 3D Printing of Nanoparticles

**R. Shireesh Kiran[1*], B. Mythili[2], T. Rama Rao[3]**

**[1,2]Department of Pharmaceutics, CMR college of pharmacy, Afflicated to JNTUH, Medchal, Kandlakoya, Hyderabad, 501401, Telangana, India.**

**[3]Professor and Principal, CMR college of pharmacy, Medchal, Kandlakoya, Hyderabad, Telangana, India.**

**[*]Corresponding Author**

**DOI: https://doi.org/10.51244/IJRSI.2025.120700111**

**Received: 14 July 2025; Accepted: 19 July 2025; Published: 06 August 2025**

## ABSTRACT

The rapid tooling and mass production are made possible by 3D printing, also known as additive manufacturing, because of its design flexibility and notable speedup of the design to manufacturing process. The avenues in material science have been opened by the use of nanoparticles into 3D printing methods, which enables the performance of high-performance functional materials with enhanced mechanical, electrical, thermal and biological properties. The 3D printing of nanoparticles is an innovative way to overcome the certain limitations through addictive manufacturing, and makes it possible to fabricate intricate structures with integrated nanoparticles layer by layer. The current approaches for adding nanoparticles into 3D printing platforms, such as inkjet, stereolithography, fused deposition modelling (FDM) and extrusion-based printing methods. In addition to the effects on the performance and structural integrity of printed products, the difficulties of nanoparticle dispersion, printability and post-processing are highlighted. The applications that showcases for nanoparticles enhancing for 3D printing are electronics, energy storage, biomedical engineering and environmental sensing. There are so many advancements in 3D printing nanoparticles from micro–nanoscale. A new era of material innovation has been ushered by the combination of additive manufacturing and nanotechnology, with 3D printing nanoparticles emerging as a game changing method for creating useful materials for the future. With additionally, this article examines the potential future paths, such as AI-driven material design, sustainable manufacturing, and 4D printing, while highlighting the difficulties with nanoparticle-based 3D printing.

**Keywords: -** 3D printing, additive manufacturing, inkjet, stereolithography, fused deposition modelling, extrusion-based printing, nanoparticle dispersion, printability, post processing.

## INTRODUCTION

Additive manufacturing or 3-Dimentional (3-D) printing has become popular lately. Most people are not aware that this technology has been invented way long before the 2nd millennium. 3-D printing has begun in the late 1980s whereby the first technique was known as the Rapid Prototyping (RP), or commonly recognized as Stereolithography (SLA) in the current term. The patent of this printing technique owned by an American developer named Charles Hull [1]. SLA printer was the first device to print an object directly from a computer (digital) file. 3-D printing only used in industries but not in the public when it started in 80s. This is due to 3-D printing offered a rapid prototyping of industrial products resulted in quick and accurate processes. The design by 3-D printing is high in accuracy, it also accomplishes design freedom where there are no barriers to the imagination. Due to this advantage, artists can now produce a physical sculpture which would otherwise be sketched on a paper. With many advantages, there are more industries are shifting from conventional manufacturing to 3-D printing technique to produce their goods. The cost of production can be reduced because a few parts can be printed into one single object compared to conventional manufacturing which only enables printing of several parts separately in addition with no tooling required [2, 3]. Therefore, this favours the manufacturing industries since saving cost could mean gaining more profit. In addition, 3-D can also print parts with complex geometries which is impossible to be produced by the traditional method [4]. This will bring advantages to the manufacturers as it is possible to produce a wide range of industrial goods such as hard tooling product like moulds. Traditionally, moulds are computer numerical control (CNC) milled either undergoing multiple design alterations, or taking weeks and months to achieve the final design. Now, 3-D printing technologies can be used instead, allowing material and waste reduction, while improving the functionality of a mould. The main improvements which can be seen in tooling products are lightweight, improved design, improved ergonomics and reduction in material waste [5]. Due to the popularity of additive manufacturing, 3-D printers are currently used as home use by people who are interested in creating their own prototypes. The technology is commonly used in automotive, architecture, healthcare, entertainment and goods industry. For example, the printing of spare parts is now possible with improved mechanical properties when using nanomaterial or composites. This can result in a stronger build-in which increases the safety aspect of the mobile in car racing and even space mission. Furthermore, 3-D printing technology can be applied in the medicine field. One of the successful examples is the printing of hearing aids which has a unique structure between different individuals [6, 7]. In addition, people are getting 3-D printed teeth which is customized to each person. Unlike the previous one-size-fits-all teeth which is uncomfortable, the 3-D printed teeth will fit nicely suited to the patients. This technology was also greatly explored in bioprinting of tissues and organs, the printing of animal tissues for drug testing and teaching purpose, skin grafting [8–11]. In combating the COVID-19 pandemic, 3-D printing shown its important role in coping up to produce medical equipment such as face shield, face mask, ventilator parts, nasopharyngeal swab, antibacterial mask and wearable device for patient [12–15, 170]. In addition, 3-D printed food can also be customized to patients suffering from dysphagia phenomenon to make food more visually appealing [16, 17]. There is still a wide application of 3-D printing yet to be explored. 3-D printing is a promising technology to print customized and high-quality products. It is believed to bring positive impacts to various sectors in the future when more fields are utilising this technology. However, the major drawback of producing 3-D printed goods is the fragility of the printed parts, as most production only focus on building prototypes rather than functional parts, since the printed objects always result in a lack of strength. Therefore, one of the promising solutions is to incorporate nanoparticles or fillers into the polymer to strengthen the printed object. Nanoparticles (NPs) are extremely tiny particles which have the size ranges from 1 to 100 nm [18]. Owing to their small size, nanoparticles have a large surface area to volume ratio which enable them to be explored in various sector. Aside from the application stated in the previous paragraph, researchers are aiming to produce a more functional object by the incorporation of nanoparticles. Most of the published review papers only discuss on the 3-D printing techniques and printing of pure materials. When 3-D printing technology was greatly explored in many sectors, a more functional prototypes are demanded and many researchers have been putting effort to develop composites with improved functionality and performance [19–22]. Therefore, this review provides an overview of the improvement and advancement in 3-D printing product which enhanced with nanoparticles. The types of 3-D printer are reviewed as the type of printers considered as a factor that influence the choice of raw materials to be printed, along with the advantages and disadvantages of each printing technique. The base materials that are commonly used in 3-D printing are analysed in Sect. 3 depending on the application accordingly. Last but not the least, the development of nanocomposites in various applications are followed by the discussion on the drawbacks that occurred and the suggestions for future steps of additive manufacturing. The technology is commonly used in automotive, architecture, healthcare, entertainment and goods industry. For example, the printing of spare parts is now possible with improved mechanical properties when using nanomaterial or composites. This can result in a stronger build-in which increases the safety aspect of the mobile in car racing and even space mission. Furthermore, 3-D printing technology can be applied in the medicine field. One of the successful examples is the printing of hearing aids which has a unique structure between different individuals [6, 7]. In addition, people are getting 3-D printed teeth which is customized to each person. Unlike the previous one-size-fits-all teeth which is uncomfortable, the 3-D printed teeth will fit nicely suited to the patients. This technology was also greatly explored in bioprinting of tissues and organs, the printing of animal tissues for drug testing and teaching purpose, skin grafting [8–11]. In combating the COVID-19 pandemic, 3-D printing shown its important role in coping up to produce medical equipment such as face shield, face mask, ventilator parts, nasopharyngeal swab, antibacterial mask and wearable device for patient [12–15, 170]. In addition, 3-D printed food can also be customized to patients suffering from dysphagia phenomenon to make food more visually appealing [16, 17]. There is still a wide application of 3-D printing yet to be explored. 3-D printing is a promising technology to print customized and high-quality products. It is believed to bring positive impacts to various sectors in the future when more fields are utilising this technology.

**History of 3D printing of Nanoparticles :-**

| | |
|---|---|
| **Origin of 3D printing** | Initially, the researchers tried adding nanoparticles to printed materials, like metal oxides, silica, and carbon nanotubes, to improve their mechanical and thermal characteristics. The foundation of 3D printing, or additive manufacturing (AM), dates back to the 1980s.<br>In the year **1984** :- Chuck Hull invented stereolithography (SLA), the first 3D printing technique, and co-founded 3D Systems.<br>**1990s–2000**s: Development of other major techniques such as Fused Deposition Modelling (FDM) by Scott Crump (Stratasys) and Selective Laser Sintering (SLS) by Carl Deckard. |
| **In 2000s - The emergence of nanoparticles in 3D printing** | The incorporation of nanoparticles into 3D printable materials began in the early 2000s, driven by a desire to enhance the functional properties of printed objects. While no single person is credited with "inventing" 3D printing *of* nanoparticles, it emerged as a convergence of two rapidly growing fields: nanotechnology and additive manufacturing.<br>**2002–2005**: Early research began exploring nanocomposite filaments and resins for use in FDM and SLA printing.<br>**2006–2010**: Academic labs started publishing on carbon nanotube-infused thermoplastics and metal oxide nanoparticles for structural reinforcement and conductivity. Nanoparticles began to be widely used in drug delivery, tissue scaffolds, and printed electronics, with research moving from experimental to application-focused. The creation of inks and nanocomposites based on nanoparticles that are suited for certain uses, such as biomedical devices, electronics, and sensors, has advanced significantly. Drug-loaded scaffolds, conductive traces, and smart materials were made possible by advances in functional printing during this time. |
| **In present**<br>**(Evolution of the field)** | In the year **2020** to **present year :-** Development of hybrid printing platforms, in-situ synthesis, and stimuli-responsive nanomaterials in additive manufacturing. Innovations in materials science, hybrid printing platforms, and in-situ nanoparticle synthesis have fueled the fast advancement of the 3D printing of nanoparticles. High-performance, adaptable components for industries like energy storage, flexible electronics, and tailored medicine are made possible in large part by it. |

**Base Materials Used In 3d Printing With Nanoparticles**

In 3D printing, the bases also referred to as binders, carriers, or matrix materials—are essential for supporting, stabilizing, and dispersing nanoparticles both during and after the printing event. The type of nanoparticle, intended use, and printing method all influence the base material selection. The most common bases used in 3D printing are;

| **2.1 Polymer Bases** (especially FDM, inkjet, and SLA) | | | | |
|---|---|---|---|---|
| **Polymer** | **Extruded temperature** | **Bed temperature** | **Function** | **Used with** |
| Polylactic acid (PLA) | 170-220$^{0\ C}$ | 20-55$^{0}$ C | Biodegradable matrix | Silver, graphene |
| Acrylonitrile | 215–250 °C | 80–110 °C | Tough and thermally | CNTs, Corbon |

| | | | | |
|---|---|---|---|---|
| Butadiene styrene (ABS) | | | stable | black |
| Polyvinyl acetate (PVA) | 160–170 °C | 40 °C | Linear polymer made by polymerizing vinyl acetate monomers | water-soluble support structure in FDM printing |
| Polyethylene terephthalate (PET) | 230-255$^0$ C | 55-75$^0$ C | Matrix / Blender | Acts as a base polymer matrix to host and uniformly distribute nanoparticles |
| Nylon | 210-250$^0$ C | 60-80$^0$C | Polymer matrix / carrier | Acts as a host matrix to embed and disperse nanoparticles |

**2.2 Solvent and ink based materials**

(especially used in inkjet or spray based 3D printing)

| **Base type** | **Nanoparticles** | **Purpose** |
|---|---|---|
| Water | $Tio_2$, graphene oxide | Eco-friendly dispersion. |
| Ethanol | Silver, CNTs | Volatile carrier and fast drying |
| Glycerol | Ceramics and metals | Viscosity control |

**2.3 Metal and alloy powders (micron + nanoparticles)**

(Especially used as a base for SLS and SLM)

| **Base metal** | **Nanoparticles mixed in** | **Applications** |
|---|---|---|
| Titanium alloys | HA, Ag, CNTs | Orthopedic implants |
| Stainless steel | $Al_2O_3$, Sic, graphene | Structural wear, resistant parts |
| Nickel alloys | Ceramic NPs, graphene | High temperature components |
| Copper | Graphene, CNTs | Electronics and heat sink |

**2.4 Ceramic and glassy bases**

(used in sintering-based printing)

| **Base ceramic** | **Nanoparticles added** | **Applications** |
|---|---|---|
| Hydroxyapatite (HA) | Ag, ZnO, $TiO_2$ | Bone implants, antibacterial parts |
| Zirconia ($ZrO_2$ ) | Graphene, CNTs | Dental, load bearing parts |
| Silica ($SiO_2$) | Metal or dye NPs | Optical, catalytic structures |

**The 3d Printing Techniques For Nanoparticles:-**

**3.1 STEREOLITHOGRAPHY (SLA) :-** The resin-based 3D printing process known as stereolithography (SLA) cures photosensitive polymers layer by layer into a solid object using ultraviolet (UV) light or lasers.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

Although SLA is widely used for microscale printing, its application to the creation or integration of nanoparticles is a new field of study and development. Silver, gold, silica, carbon nanotubes, $TiO_2$, and graphene are among the nanoparticles that are mixed into photocurable resins. Printing materials are subsequently made from these nanocomposite resins. The precision is high in stereolithography. The models, prototypes, and patterns are used as a printed objects for this technique in 3D printing.

**Advantages of stereolithography with nanoparticles :-**

1. SLA is useful for directing the placement of nanoparticles since it can reach micron to sub-micron precision.
2. SLA makes it possible to create complex structures that can act as scaffolds or nanoparticle carriers.
3. It is less time consuming, cheaper and excellent surface finishing.
4. It has smooth surface.

**Applications :-**

1. It is Used in bone regeneration, cartilage repair, and soft tissue engineering.
2. SLA enables precise fabrication of microscale or nanoscale carriers loaded with drug-releasing nanoparticles.
3. pH-responsive or temperature-sensitive nanoparticles can be incorporated for controlled or targeted release.
4. It incorporates the metallic nanoparticles or quantum dots into SLA-printed parts can modify light absorption, reflection, and transmission.
5. SLA printed structures with conductive nanoparticles can serve as flexible or wearable sensors.

**3.2 Fused Deposition Modelling (Fdm) :-** Fused Deposition Modelling (FDM) is a popular 3D printing method that creates 3D objects by heating and extruding thermoplastic filament layer by layer. Creating nanocomposite filaments—filaments impregnated with nanoparticles to improve functionality or material properties—is the standard procedure when using nanoparticles in FDM. The mechanism of FDM is When the melted thermoplastic is put in the designated areas, the part is constructed layer by layer. The fresh layer will adhere to the previous layer once each layer has solidified. Using this method, an object is printed from bottom to top. The models and moderate prototyping are used to prepare as a printed objects for the modelling. The precision is lower than compared to stereolithography.

**Advantages of FDM with nanoparticles :-**

1. Cost-effective
2. Wide material compatibility
3. Easy to scale
4. Allows multifunctional parts with enhanced properties

**Applications :-**

1. Nanoparticles embedded in biodegradable filaments enable gradual drug release in medical implants or stents.
2. Nanocomposites help create lightweight, EMI-shielded enclosures for electronic devices.
3. Adding nanoparticles like nanoclay, graphene, or carbon black improves: Tensile strength. Thermal resistance, Durability of printed parts.
4. FDM-printed filters with $TiO_2$ or ZnO can degrade pollutants under UV light.
5. Nanoparticle-loaded membranes help in water filtration, oil spill cleanup, or heavy metal adsorption

**3.3 <u>SELECTIVE LASER SINTERING (SLS)</u> :-** A high-power laser, usually $CO_2$, is used in Selective Laser Sintering (SLS), a powder-based 3D printing method, to fuse powder particles layer by layer to create three-

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

dimensional objects. Although SLS is mainly applied to powders that are polymeric, metallic, or ceramic, adding nanoparticles to the process creates fascinating opportunities for precision engineering and enhanced material functioning. Selective laser sintering works by joining small particles together with heat from a high-power laser beam. Granular materials are employed, with nylon (PA) polymer serving as the primary component in SLS printers. Prosthetics, dental retainers, hearing aids, automotive and aerospace components are used to prepare for the printed objects. The precision is high.

**Advantages of SLS with nanoparticles :-**

1. For complex parts, structure support is not necessary.
2. Cut back on the quantity of raw materials
3. Reduced manufacturing costs
4. Very little post-processing
5. It is possible to print structures that need a lot of intricacy.
6. Less time-consuming
7. The printed parts are strong and long-lasting.
8. It can be used to print a variety of materials, including metal structures, glass, ceramic, and plastic.

**Applications :-**

1. SLS produces prototypes for medical devices, functional models for surgeries, and even scaffolds for tissue engineering.
2. SLS is used for prototyping, producing small to medium-batch components, and even manufacturing spare parts for classic cars.
3. SLS is ideal for creating jigs, fixtures, tools, and investment casting patterns.
4. SLS is used for producing functional proof-of-concept models, design evaluation models, and short-run end-use components.
5. SLS can be used for creating large quantities of components efficiently and at a low cost per part.

**3.4 SELECTIVE LASER MELTING (SLM) :-** In the sophisticated powder bed fusion (PBF) method known as Selective Laser Melting (SLM), metal powders are melted layer by layer by a high-energy laser (usually a fiber laser) to create fully dense 3D objects. In contrast to SLS, which sinters, SLM melts the material completely, creating stronger metallic pieces that are frequently of wrought grade. The mechanism Powder bed fusion is the umbrella term for the process. Metals are utilized as the feedstock type. The precision is high.

**Advantages of SLM with Nanoparticles :-**

1. A wide variety of metals are available.
2. Capable of recognizing intricate interior features or forms.
3. shortened lead times because tooling is not required.
4. Manufacturing several pieces simultaneously.

**Applications :-**

1. SLM of nickel-based superalloys with nano reinforcements provides high-temperature fatigue resistance

2. SLM can produce metallic foams embedded with platinum, palladium, $TiO_2$ nanoparticles.
3. It is Used for chemical reactors, hydrogen production, or $CO_2$ reduction.
4. It Enables the real-time stress, temperature, or strain monitoring in aerospace or structural parts.

**3.5 INKJET PRINTING:-** The Tiny droplets of ink containing nanoparticles are ejected from a printhead and deposited layer by layer to create a three-dimensional structure using the inkjet printing technology for 3D printing with nanoparticles. A printhead is filled with a liquid ink that contains scattered nanoparticles. The ink droplets are ejected via: thermal actuation (tiny heaters create vapor bubbles to force out droplets) Piezoelectric actuation (crystals deform under voltage to expel droplets). The Droplets are deposited precisely onto a

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

substrate, layer-by-layer. Post-processing (e.g. drying, sintering, or curing) solidifies the nanoparticles into functional structures. The droplet volume of inkjet is 1-100 picolitres.

**Advantages of inkjet with nanoparticles:-**

1. non contact printing.
2. Supports multi material and gradient designs.
3. Minimizes waste, especially for expensive nanoparticles.
4. It is scalable.

**Applications :-**

1. Inkjet printing is used to create microscale Li-ion batteries by depositing nanoparticles of $Li_4Ti_5O_{12}$ (LTO) as the anode and $LiFePO_4$ (LFP) as the cathode. This method allows for the precise placement of nano-sized materials to achieve a small feature size, as low as 1μm.
2. Inkjet printing is employed for various biomedical applications, including tissue engineering, artificial organs, and artificial skin. It can also be used to create drug delivery systems, implants, and devices for monitoring heart activity using flexible sensors and machine learning.
3. Inkjet printing finds applications in creating microfluidic devices, electronic circuits, and even smart devices. It is also used in the production of microlenses, enabling rapid and cost-effective fabrication.

**Applications Of Nanoparticles Based 3d Printing :-**

The applications of 3D printing of nanoparticles in the fields of electronics, energy storage, medical, and aerospace have been listed from the recent advancements, such as;

**Electronics :-**

1. **High-Conductivity Inks:** Nanoparticles of metals like silver, copper, and gold, as well as conductive nanomaterials like carbon nanotubes and graphene, are used to create conductive inks for 3D printing electronic circuits, sensors, and interconnects with enhanced conductivity and finer features.

2. **Flexible and Wearable Electronics:** Nanocomposites enable the fabrication of flexible and stretchable electronic components for wearable devices and bendable displays.

3. **Miniaturization of Devices:** Nanomaterials facilitate the creation of miniaturized electronic devices, including micro-batteries and micro-supercapacitors, with improved performance.

4. **Multifunctional Materials:** Combining different nanomaterials within a 3D-printed structure allows for the creation of devices with integrated functionalities, such as sensors with embedded circuitry.

**Energy Storage :-**

1. **High-Performance Batteries:** Nanoparticles enhance the electrode materials in 3D-printed batteries, leading to higher energy density, faster charge-discharge rates, and improved cycle life. Examples include lithium-ion batteries with graphene or carbon nanotube-enhanced electrodes.

2. **Supercapacitors with Enhanced Properties:** 3D printing with nanomaterials like graphene and carbon nanotubes allows for the fabrication of supercapacitors with increased surface area, leading to higher power density and faster energy delivery.

3. **Customizable Energy Storage Devices:** 3D printing enables the creation of energy storage devices with complex and customized geometries, optimized for specific applications and integration into various devices.

4. **Flexible Energy Storage:** Nanocomposites are used to 3D print flexible batteries and supercapacitors for wearable electronics and other flexible devices.

**Medical :-**

1. **Personalized Drug Delivery Systems:** 3D printing with nanoparticles allows for the creation of drug delivery systems with tailored release profiles and dosages, customized for individual patient needs.

2. **Enhanced Tissue Engineering Scaffolds:** Nanoparticles incorporated into 3D-printed scaffolds improve cell adhesion, proliferation, and differentiation, promoting tissue regeneration and repair.

3. **Antimicrobial Implants and Devices:** Silver nanoparticles are added to 3D-printed medical implants and devices to impart antimicrobial properties, reducing the risk of infection.

4. **Bioinks for Bioprinting:** Nanomaterials enhance the mechanical strength and biocompatibility of bioinks used in 3D bioprinting for creating complex tissue constructs and organ models.

5. **Theranostics:** Nanoparticles can be integrated into 3D-printed devices for simultaneous diagnosis and therapy, such as drug-eluting implants with imaging capabilities.

**Aerospace :-**

1. **Lightweight and High-Strength Structural Components:** Nanoparticles, such as carbon nanotubes and ceramic nanoparticles, reinforce 3D-printed aerospace components, reducing weight while maintaining or enhancing strength and stiffness, leading to improved fuel efficiency.

2. **Advanced Thermal Management:** Nanomaterials with high thermal conductivity are used in 3D-printed parts for efficient heat dissipation in aerospace electronics and engine components.

3. **Electromagnetic Interference (EMI) Shielding:** Conductive nanoparticles incorporated into 3D-printed materials provide EMI shielding for sensitive aerospace electronics.

4. **Radiation Shielding:** Certain nanomaterials can be integrated into 3D-printed spacecraft components to offer enhanced protection against radiation in space.

5. **Customized and Optimized Designs:** 3D printing with nanomaterials enables the creation of complex, optimized geometries for aerospace parts, reducing material waste and improving performance.

**Notable Patents In 3d Printing Of Nanoparticles :-**

Some of the most notable patents in 3D printing of nanoparticles are ;

| Sno | Author name | Patent no | Summary |
|---|---|---|---|
| 1. | **Yiliyang wu** | **US9505058B2** | This invention focuses on stabilized metallic nanoparticles, like silver, for use in 3D printing. The nanoparticles are designed to be sintered using low-energy light sources, enabling the creation of conductive components without high-temperature processes. |
| 2. | **William Niedermayer** | **WO2023076095A1** | This patent introduces a 3D printing composition that incorporates light-scattering metal nanoparticles. These nanoparticles enhance the curing process during printing by scattering UV light, leading to faster and more uniform curing of printed layers. |
| 3. | **James elmor abbott** | **US20170252974A1** | This method involves using a build material composed of inorganic particles, such as metals or ceramics, combined |

| | | | |
|---|---|---|---|
| | | | with polymers. The approach allows for the creation of composite materials with tailored properties for various applications. |
| 4. | **Hemant bheda** | **US20160297142A1** | This patent describes a method for additive manufacturing that involves depositing layers of inks containing thermopolymers and nano-fillers (such as carbon nanotubes), followed by exposure to microwave radiation to cure the layers. The process allows for the creation of composite materials with enhanced properties. |

**The Future Paths In 3d Printing Of Nanoaprticles :-**

**Functional Nanocomposites :-** Nanoparticles will be used not just for strength but to add new properties like conductivity, magnetism, or self-healing ability to printed objects.

**4D Printing :-** Combining nanoparticles with stimuli-responsive materials will enable objects to change shape or function over time (e.g., heat-activated implants or soft robotics).

**Bioprinting and Medicine :-** Nanoparticle-enhanced bioinks will advance tissue engineering, drug delivery, and customized medical implants with smart or antibacterial properties.

**Nanoelectronics :-** Printing flexible circuits, sensors, and devices using conductive nanoparticles like graphene, silver, or CNTs for applications in wearables and smart devices.

**High-Resolution and Hybrid Printing :-** New techniques (e.g., two-photon lithography, inkjet + FDM hybrids) will allow submicron printing of complex, multi-material structures.

**Sustainable Nanoprinting :-** Using biodegradable polymers and green nanoparticles will promote eco-friendly printing for packaging, environmental sensors, and filters.

**AI-Driven Design :-** AI and machine learning will optimize material formulations and print parameters, making printing faster, smarter, and more efficient.

## CONCLUSION

The use of nanoparticles into 3D printing methods has opened up new avenues for material science research and development, allowing for the creation of highly customizable and functional structures with improved thermal, mechanical, and electrical characteristics. Advanced applications in the medical, aerospace, and electronics sectors have resulted from the successful incorporation of nanoparticles into techniques including inkjet printing, stereolithography, and fused deposition modelling. At the nanoscale, maintaining print resolution, avoiding aggregation, and attaining uniform dispersion continue to be difficult tasks despite the encouraging developments. The full potential of nanoparticle-enhanced 3D printing will require future research on material compositions, printing accuracy, and scalable production techniques. This will pave the way for the development of next-generation smart materials and devices.

## REFERENCES

1. Xu, W., Jambhulkar, S., Ravichandran, D., Zhu, Y., Kakarla, M., Nian, Q., ... & Song, K. (2021). 3D printing-enabled nanoparticle alignment: a review of mechanisms and applications. Small, 17(45), 2100817.
2. Tan, H.W., An, J., Chua, C.K. and Tran, T., 2019. Metallic nanoparticle inks for 3D printing of electronics. Advanced Electronic Materials, 5(5), p.1800831.

3. Kwon, O., Yoon, C., Ham, S., Park, J., Lee, J., Yoo, D. and Kim, Y., 2017. Characterization and control of nanoparticle emission during 3D printing. Environmental science & technology, 51(18), pp.10357-10368.
4. Francis, V., Garg, S., Saxena, K.K., Jain, P.K., Lade, J. and Kumar, D., 2022. Effect of chemical and heat treatment on 3D printed parts: Nanoparticles embedment approach. Advances in Materials and Processing Technologies, 8(sup4), pp.2277-2288.
5. Fantino, E., Chiappone, A., Roppolo, I., Manfredi, D., Bongiovanni, R., Pirri, C.F. and Calignano, F., 2016. 3D Printing of Conductive Complex Structures with In Situ Generation of Silver Nanoparticles. Advanced materials (Deerfield Beach, Fla.), 28(19), pp.3712-3717.
6. Kim, Y., Yoon, C., Ham, S., Park, J., Kim, S., Kwon, O. and Tsai, P.J., 2015. Emissions of nanoparticles and gaseous material from 3D printer operation. Environmental science & technology, 49(20), pp.12044-12053.
7. Momper, R., Landeta, A.I., Yang, L., Halim, H., Therien-Aubin, H., Bodenschatz, E., Landfester, K. and Riedinger, A., 2020. Plasmonic and semiconductor nanoparticles interfere with stereolithographic 3D printing. ACS Applied Materials & Interfaces, 12(45), pp.50834-50843.
8. Pawar, Amol A., Gabriel Saada, Ido Cooperstein, Liraz Larush, Joshua A. Jackman, Seyed R. Tabaei, Nam-Joon Cho, and Shlomo Magdassi. "High-performance 3D printing of hydrogels by water-dispersible photoinitiator nanoparticles." Science advances 2, no. 4 (2016): e1501381.
9. Kwon, O., Yoon, C., Ham, S., Park, J., Lee, J., Yoo, D. and Kim, Y., 2017. Characterization and control of nanoparticle emission during 3D printing. Environmental science & technology, 51(18), pp.10357-10368.
10. Pawar, A.A., Saada, G., Cooperstein, I., Larush, L., Jackman, J.A., Tabaei, S.R., Cho, N.J. and Magdassi, S., 2016. High-performance 3D printing of hydrogels by water-dispersible photoinitiator nanoparticles. Science advances, 2(4), p.e1501381.
11. Okafor, O., Weilhard, A., Fernandes, J.A., Karjalainen, E., Goodridge, R. and Sans, V., 2017. Advanced reactor engineering with 3D printing for the continuous-flow synthesis of silver nanoparticles. Reaction Chemistry & Engineering, 2(2), pp.129-136.
12. Kunchala, Pragnya, and Keerti Kappagantula. "3D printing high density ceramics using binder jetting with nanoparticle densifiers." Materials & Design 155 (2018): 443-450.
13. Jelinski, L., 1999. OVERVIEW OF NANOPARTICLE/NANOTECHNOLOGY RESEARCH IN JAPAN. Nanostructure Science and Technology: R & D Status and Trends in Nanoparticles, Nanostructured Materials and Nanodevices, p.243.
14. Fantino, E., Chiappone, A., Calignano, F., Fontana, M., Pirri, F., & Roppolo, I. (2016). In situ thermal generation of silver nanoparticles in 3D printed polymeric structures. Materials, 9(7), 589.
15. Ni, Rongping, et al. "3D printing of resin composites doped with upconversion nanoparticles for anti-counterfeiting and temperature detection." Optics express 26.19 (2018): 25481-25491.
16. Ni, R., Qian, B., Liu, C., Liu, X., & Qiu, J. (2018). 3D printing of resin composites doped with upconversion nanoparticles for anti-counterfeiting and temperature detection. Optics express, 26(19), 25481-25491.
17. Dudukovic, N. A., Wong, L. L., Nguyen, D. T., Destino, J. F., Yee, T. D., Ryerson, F. J., ... & Dylla-Spears, R. (2018). Predicting nanoparticle suspension viscoelasticity for multimaterial 3D printing of silica–titania glass. ACS Applied Nano Materials, 1(8), 4038-4044.
18. Kim, K., Zhu, W., Qu, X., Aaronson, C., McCall, W.R., Chen, S. and Sirbuly, D.J., 2014. 3D optical printing of piezoelectric nanoparticle–polymer composite materials. ACS nano, 8(10), pp.9799-9806.
19. Elliott, Amelia McDow. The effects of quantum dot nanoparticles on the polyjet direct 3D printing process. Virginia Polytechnic Institute and State University, 2014.
20. Kraus, Tobias, Laurent Malaquin, Heinz Schmid, Walter Riess, Nicholas D. Spencer, and Heiko Wolf. "Nanoparticle printing with single-particle resolution." Nature nanotechnology 2, no. 9 (2007): 570-576.
21. Liu H, Webster TJ. From nano to micro: nanostructured titania/PLGA orthopedic tissue engineering scaffolds assembled by three-dimensional printing. American Institute of Chemical Engineers; 2006.
22. Godlinski, D., Petzoldt, F., & Morvan, S. (2004). PM Functional Materials: Tailored Functional Gradients by 3D-Printing using Metal Powder and Nano-particulate Inks. In European Congress and

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

Exhibition on Powder Metallurgy. European PM Conference Proceedings (Vol. 4, p. 1). The European Powder Metallurgy Association.
23. Calvert, Paul. "Inkjet printing for materials and devices." Chemistry of materials 13, no. 10 (2001): 3299-3305.
24. Liu, H. and Webster, T.J., 2006. Ceramic/polymer nanocomposite tissue engineering scaffolds for more effective orthopedic applications: from 2D surfaces to novel 3D architectures. MRS Online Proceedings Library (OPL), 950, pp.0950-D10.
25. CBramic, N., Compesites, P. and Scaffoids, E., 2007. Biomatoriais at Matoriais. Advanced Materials & Processes.
26. Chovancova, V., Pekarovicova, A. and Fleming, P.D., 2005, January. Hot melt inks for 3D printing. In NIP & Digital Fabrication Conference (Vol. 21, pp. 143-147). Society of Imaging Science and Technology.
27. Joseph, Shine, Stella Quiñones, Frank Medina, and Ryan Wicker. "Effect of surface preparation methods on mechanical properties of 3D structures fabricated by stereolithography and 3D printing for electroless Ni plating." (2007).
28. Crane, N.B., Sachs, E.M. and Frank, A., 2004. Strengthening porous skeletons by metal deposition from a nanoparticle suspension. MRS Online Proceedings Library (OPL), 860, pp.LL3-3.
29. İşçimen, Elif Meltem. "Pickering emulsions from rice protein-xanthan gum nanoparticles at different oil content: emulsion properties and using producing cake as a fat replacer." Harran Tarım ve Gıda Bilimleri Dergisi 29, no. 1: 162-176.
30. Heuer, A.H., 1996. Biomimetic strategies and materials processing. Biomimetic materials chemistry, p.41.