*Mustansiria Dental Journal*
*DOI: 10.32828/mdj.v22i1.1261*

*E- ISSN: 2618-0944*
*P- ISSN: 1813-8500*

# Nanoparticle-Reinforced 3D-Printed Dental Resins: Reinforcement Mechanisms, Manufacturing Challenges, and Property Outcomes: A Narrative Review

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***Received:*** *13/11/2025;* ***Accepted:*** *27/06/2026;* ***Published:*** *30/06/2026*

## Abstract

**Background:** Recent developments in manufacturing technology have brought three-dimensional (3D) printing as an efficient method for directly fabricating products from computer-aided design (CAD) data. This technology has attracted much attention in dentistry and is now employed in numerous fields, such as prosthodontics, orthodontics, and implant dentistry. Although there are several studies on the reinforcement of 3D-printed dental resins using nanoparticles, there are still few narrative reviews that provide detailed discussion on the reinforcement tactics and the related manufacturing issues. Purpose: The present study covers the existing information on 3D-printed dental resins, highlighting the use of nanoparticles as a reinforcing method, the possible constraints of incorporating nanoparticles, and the manufacturing processes involved in the production of the materials. Furthermore, the influence of these alterations on the mechanical and physical behavior of printed dental materials is also examined to provide a better understanding of recent advances and possible future avenues of research. **Methods:** The relevant studies were obtained by studying the articles published in 2010-2025 in the databases of Scopus, Pubmed, and Google Scholar. The inclusion criteria focused on research that evaluated the introduction of nanoparticles in 3D-printed dental resins to enhance mechanical, surface or functional qualities. Inclusion of studies having a defined experimental procedure and quantitative results. **Results:** The nanoparticles tested were $ZrO_2$, YSZ, $SiO_2$, ZnO, $TiO_2$, $Al_2O_3$, and Ag and several mechanical, surface, and antibacterial properties of 3D printed dental resins were improved with minimal, or no change in certain properties.

DOI: 10.32828/mdj.v22i1.1261

The effect was also found to rely on the type and concentration of the nanoparticles and the preparation and printing processes utilized. But these developments have sometimes led to problems with resin formulation, printing accuracy and post-processing, which have to be carefully calibrated for clinical use. **Conclusions:** Enhanced some mechanical, surface and antibacterial properties, as well as the potential for function and material development, due to the addition of nanoparticles to the 3D-printed dental resins. More research is needed to fully examine the long-term effectiveness of different types and doses of nanoparticles, their therapeutic significance and any health hazards related with their use.

**Keywords**: Dentistry, 3D Printed resin material, Nanofillers, Mechanical properties, Material reinforcement, Nanoparticles.

**Introduction:**

3D-printed resin has become a preferred option for fabricating prostheses in patients with partial or complete edentulism. Although compression and injection molding are widely used, both methods present several drawbacks that limit their performance. Researchers have sought to overcome these problems, particularly those related to the number of clinical visits required, the weight of maxillofacial prostheses, the tendency for bacterial buildup, and the considerable shrinkage that occurs during polymerization (Fatalla et al., 2020; Priya & Muthukumar, 2023). With the advent of digital dentistry, major solutions have been developed in the field to overcome these limitations of the conventional method. The two main approaches of computer-aided design (CAD) and computer-aided manufacturing (CAM), which Goodacre described as disruptive technology in 1990, are subtractive and additive (Goodacre et al., 2016). At first, the subtractive method predominated, but the additive process emerged as a result of its drawbacks. In the fields of dentistry, engineering, and medicine, this sophisticated technique is known as the CAM step and serves as an adaptable tool as it constructs components incrementally (Dimitrova et al., 2023). The additive technique utilizes three-dimensional (3D) model data to accurately integrate components, facilitating the broad use of different materials, such as metals, ceramics, and polymers (Dimitrova et al., 2023). Stereolithography (SLA) employs ultraviolet light to create intricately detailed models, facilitating the accurate production of small items, typically measuring approximately 50 mm. The use of rapid photo-curing significantly improves the efficiency of model creation (Chen et al., 2019).

The technology of 3D printing is independent and easy to utilize. That facilitates the fabrication of designed porous structures, suitable for embedding autonomous healing polymers that are enhanced with nanoparticles (Ullah et al., 2020).

Despite the obvious benefits of 3D printing, the inherent characteristics of 3D-printed resins still have limitations when in comparison to traditional materials like heat-cured acrylic or CAD-CAM resins (Zaharia

DOI: 10.32828/mdj.v22i1.1261

et al., 2017; Al-Qarni & Gad, 2022). To lower these limitations, researchers have investigated nanoparticle reinforcement. Because of their significant resilience to corrosion and longevity, their properties can be improved by changing their dimensions (Ali Sabri et al., 2021).

The mechanical, biological, and physical properties can be imparted by polymeric nanoparticles, which could include nanoscale elements into the matrix of polymers (Adhikari & Michler, 2009; Ahmed et al., 2016). Material properties have been significantly improved by adding various nanofillers to 3D-printed resins (Altarazi et al., 2024; Gad et al., 2022) The characteristics of the finished 3D-printed material are significantly affected by the kind, size, and composition of the nanoparticles (Altarazi et al., 2024).

Numerous studies have investigated the incorporation of nanoparticles into 3D-printed dental resins, although the outcomes differ significantly based on the type of nanofiller, its concentration, and the printing settings. A complete narrative review is needed to summarize the present evidence, analyze reinforcing processes and highlight any limits. The aim of this study is to clarify the effect of different types and compositions of nanoparticles on the mechanical and physical properties of 3D printed methacrylate-based dental resins.

A complete narrative review is necessary to summarize existing knowledge, assess reinforcing mechanisms, and identify potential limitations. This research seeks to elucidate the impact of various types and compositions of nanoparticles on the mechanical and physical properties of 3D-printed methacrylate-based dental resins.

**Methodology**

A selective literature search was carried out in databases including PubMed, Scopus and Google Scholar using the keywords, “3D printing,” “nanoparticles,” “mechanical characteristics” and “dental resin.” The search included English-language articles published from 2010 to 2025 investigating 3D-printed dental resins, with a particular focus on studies that used nanoparticles to analyze their mechanical, surface, and antibacterial properties. Articles published before the specified search period, those not in English, research utilizing subtractive methods, and studies unrelated to dental applications were excluded. A total of 70 non-duplicate articles were found, and only 18 of them were relevant. The remaining studies were either not directly related to 3D-printed dental resin materials or did not concentrate on denture base applications.

**Application of Nanotechnology in 3D-Printed Dental Resins**

Nanodentistry has opened up new ways to make dental materials stronger by using novel concepts. In the past few years, many researchers focused on enhancing resin-based restorative materials by adding different kinds of fillers, including fibers and nanoparticles, utilizing various reinforcement techniques (Majeed et al., 2024; Alqutaibi et al., 2023; Rooney et al., 2024; Velo et al., 2025). Among the nanoparticles studied, aluminum oxide ($Al_2O_3$), zirconium dioxide ($ZrO_2$), titanium dioxide ($TiO_2$), silicon dioxide ($SiO_2$), zinc oxide (ZnO), and silver (Ag) have received particular attention. The final performance of the polymer nanocomposite depends largely on how the polymer matrix interacts with the nanoparticles, a relationship influenced by their type, amount, particle size, and morphology

DOI: 10.32828/mdj.v22i1.1261

(Majeed et al., 2024; Alhareb et al., 2016; Aszrin et al., 2017). Nanotechnology has improved the mechanical and physical properties of polymers such as PMMA by mixing different nanoparticles. Nanoparticles (NPs) reinforce materials and increase their overall performance (Altaie., 2023).

The dimension of nanomaterial substances ranges from 0 to 100 nanometers. Their particular features often exceed those found in the bulk form of the substance. The increased surface area and quantum effects are two elements that contribute to this improvement. Reducing a substance to the nanoscale enhances its surface area, allowing for increased contact between particles. At this scale, quantum effects affect optical, electrical, and magnetic properties differently than in bigger objects (Quan et al., 2020). Typical PMMA denture base resins exhibit poor surface characteristics and inadequate mechanical properties, including low flexural strength, hardness, and resistance to fracture and impact. To achieve optimal performance, PMMA therefore requires reinforcement. Nanotechnology plays a crucial role in this reinforcement by offering multiple potential advantages for dental applications. Polymeric nanocomposites, which incorporate nanoscale components into the polymer matrix, have demonstrated the potential to enhance material properties (Gad & Al-Thobity, 2019). Similar reinforcement strategies have also been applied to 3D-printed methacrylate-based dental resins to overcome their inherent limitations (Altarazi et al.,2024). Nanoscale reinforcing agents possess significant potential in altering the physical, mechanical, and biological properties of materials, facilitating the creation of innovative nanocomposites. The final qualities of these composites are closely linked to the properties, structure, and size of the nanoparticles that are used. The use of metal oxides to improve PMMA has made significant improvements in its physical and mechanical properties. Nano-fillers are more stable and better at handling heat than PMMA that has not been reinforced. This is because their particles are smaller, their surface area is larger, and they are spread out more evenly. This might be good for the oral health of the mouth and the way dentures work (Ali Sabri et al., 2021). Although these findings primarily relate to conventionally processed PMMA, similar nanofiller-based reinforcement concepts have been extended to 3D-printed methacrylate-based dental resins in recent studies.

**Highlights of the literature review**

1. The most widely used materials are polymers because they are simple to process and may be cured layer by layer to get the required shape. Nevertheless, they encounter numerous challenges, including restricted capabilities and the requirement for characteristics customized for certain uses (Siripongpreda et al., 2023).
2. A simple yet efficient method of adding or improving functional qualities, such as Biocompatibility, structural, physical, mechanical, thermal, and electrical conductivity, is the introduction of nanopowder into polymers (Korčušková et al., 2022; Siripongpreda et al., 2023).
3. A number of limitations arise when addition of nanomaterials in large quantities (solid loading), such as printability, precision, sedimentation, light transmission efficiency, mixture density, viscosity, and

DOI: 10.32828/mdj.v22i1.1261

the platform's ability to penetrate the mixture, all of which can lead to printing failure (Al-helli et al., 2025).

**Types of nanofillers**

Nanofillers are incorporated into dental resin materials based on their chemical composition and morphology.

Chemically, they are classified into inorganic nanofillers, such as titanium dioxide ($TiO_2$), silica ($SiO_2$), zirconia ($ZrO_2$), zinc oxide (ZnO), alumina ($Al_2O_3$), and iron oxide ($Fe_2O_3$, $Fe_3O_4$), which primarily improve mechanical properties (Aszrin et al., 2017; Fatalla et al., 2020). All relevant information was summarized in Table 1.

According to morphology, nanofillers can be divided into nanoparticles, nanofibers, and nanoclusters. The nanofibers are particularly interesting, which allow better reinforcement of the resin matrix. Depending on the desired use, nanofillers can function as optical, bioactive/antibacterial, or reinforcing additives (Nazockdast, 2016).

The geometric characteristics of nanofillers, including size, shape, aspect ratio, and dispersion, are termed their morphology. These characteristics affect the mechanical, thermal, electrical, and optical characteristics of the composite as well as how the nanoparticles interact with the resin matrix (Motloung et al., 2021).

**Zirconium oxide ($ZrO_2$) nanoparticles**

It is a ceramic biomaterial widely used in dentistry owing to its superior mechanical strength, fracture resistance, chemical stability, and aesthetic qualities. $ZrO_2$, in nanoparticle form, has been incorporated into dental resin materials as a reinforcing agent to improve mechanical properties such as flexural strength, impact resistance, and surface hardness, making it suitable for denture base and provisional restorative applications (Wang et al., 2016; Gad et al., 2019; Albasarah et al., 2021; Fareed et al., 2023). This study (AlGhamdi et al., 2024) revealed that the addition of $ZrO_2$ nanoparticles into 3D-printed provisional resins markedly improved flexural strength; however, the extent of enhancement was dependent upon printing orientation, suggesting that both material composition and manufacturing parameters are essential in influencing mechanical performance. The incorporation of $ZrO_2$ nanoparticles into 3D-printed denture base materials markedly diminished the adherence of Candida albicans, with the antifungal effect increasing in a concentration-dependent manner (Ibrahim, 2024; Fareed et al., 2023). An enhancement in tensile strength was observed with increased nanoparticle concentration (Ibrahim, 2024). $ZrO_2$ nanoparticles improved the mechanical and antifungal properties of 3D-printed denture base resins; however, certain limits have been noted. Elevated concentrations of $ZrO_2$ can result in particle agglomeration, thereby diminishing the homogeneity of reinforcement and marginally affecting mechanical performance (Ibrahim, 2024; Khattar et al., 2023). The addition of these nanoparticles can increase the viscosity of the resin, thereby influencing printability and flow characteristics during 3D printing (AlGhamdi et al., 2024; Sulaiman et al., 2024).

**Yttria-stabilized zirconia nanoparticles**

YSZ nanoparticles are a promising candidate due to their biocompatibility; they

DOI: 10.32828/mdj.v22i1.1261

are suitable for use in denture materials, have exceptional chemical stability, and have high mechanical strength (Maridurai et al., 2016; Chandra et al., 2010). The incorporation of YSZ nanoparticles into 3D-printed denture base resins resulted in enhancements to the flexural strength, impact strength, and hardness of the 3D printed denture base resin at concentrations of 1–3 wt.%, and the thermal conductivity was enhanced in a concentration-dependent manner. In addition, compared to the unmodified resin, these changed groups displayed a notable reduction in surface irregularity, suggesting that they performed better mechanically and in surface performance (Majeed, 2025). Despite the favorable improvements observed at low concentrations, the incorporation of YSZ nanoparticles at higher loadings did not result in proportional enhancements in flexural or thermal properties. This behavior may be attributed to nanoparticle agglomeration and reduced homogeneity within the resin matrix, which can negatively influence stress distribution and material processability (Majeed, 2025).

**Silicon-dioxide ($SiO_2$) nanoparticles**

It has been previously established the introduction of silicon dioxide nanoparticles into 3D-printed denture base resins enhances the thermal and physical qualities of the resultant composite material. This results from elevated surface energy, extensive surface area, and strong contact with the polymer (Gad et al., 2022). Moreover, incorporating silicon dioxide nanoparticles into 3D-printed denture base resins improves mechanical and surface properties in a concentration-dependent manner, with optimal enhancements observed at lower filler concentrations, which help maintain surface smoothness and polymerization efficiency (Gad et al., 2022).

One of the main reasons why 3D-printed resin has better qualities than traditional resin is its high filler content. Photocurable polymers suitable for vat photopolymerization 3D printing were developed by incorporating amorphous silica fillers of two dimensions, nano-fillers and micro-fillers, into an acrylic resin matrix. The findings show that when filler content increases, mechanical characteristics clearly improve. Such as Vickers hardness, flexural strength, and flexural modulus. The results indicate no significant variation in the conversion rate between the resin reinforced with fillers and the resin without fillers. Showing that the experimental 3D-printed resin's polymerization efficiency was unaffected by the addition of fillers (Karntiang et al., 2025). According to Gad et al. (2022) and Karntiang et al. (2025), the incorporation of $SiO_2$ nanoparticles at higher concentrations can lead to nanoparticle agglomeration, which may reduce the uniformity of the composite and limit improvements in mechanical and surface properties. Additionally, increasing filler content excessively may affect the viscosity of the resin and reduce printing accuracy, making the 3D printing process less precise.

**Zinc Oxide (ZnO) nanoparticles**

Recently, ZnO nanoparticles have gained greater attention as multipurpose inorganic nanoparticles due to their special optical, biochemical, electrical, biological, biocompatible, cost-effective, non-hazardous, and environmentally stable properties (Altarazi et al., 2024). Zinc oxide (ZnO) nanoparticles have been reported to enhance the mechanical and physical properties of denture base resins,

DOI: 10.32828/mdj.v22i1.1261

particularly heat-cured PMMA, owing to their reinforcing effect (Salahuddin et al., 2018; Vıkram et al., 2020). Zinc oxide nanoparticles have been included to improve the mechanical properties of 3D printed denture base resin. Priya & Muthukumar, (2023). Enhancement of microhardness and tribological properties of 3D printed denture resin by reinforcement of ZnO nanoparticles. The authors attributed the gains to the reinforcing effect of the ZnO nanoparticles in the polymer matrix but observed that benefits were concentration dependent as too high a nanoparticle loading could lead to poor homogeneity of the material due to agglomeration of the particles.

**Silver Nanoparticles (AgNPs)**

Silver nanoparticles are among the most commonly used nanofillers in different products because of their antibacterial properties and lower toxicity than ionic silver (Altarazi et al., 2024). However, silver nanoparticles have two major issues. These are aggregation and bad distribution of the nanoparticles in the composite material. Some of the recommended treatments to overcome this problem are surface graft modification and silane coupling agent therapy (Ai et al., 2017). Aati et al. (2022) reported a research of a novel strategy for optimizing 3D printed denture base material. Adding silver nanoparticles to mesoporous silica carriers increased hardness, crack resistance, and antibacterial characteristics. At higher filler concentrations (≥1 wt%), there was a negligible decrease in flexural strength compared to the control material, indicating that excessive Ag/MSN may slightly compromise mechanical integrity. Additionally, surface roughness increased significantly at these higher concentrations, which may negatively affect clinical performance and microbial adhesion risk. These effects are likely related to nanoparticle distribution and agglomeration within the resin matrix at elevated loadings (Aati et al., 2022).

**Titanium Dioxide ($TiO_2$) nanoparticles**

Denture base materials are widely studied with the excellent qualities of titanium dioxide (TiO2) such as low cost, chemical stability, non-corrosive nature, biocompatibility and antibacterial activity against gram-positive and gram-negative bacteria. The addition of $TiO_2$ nanoparticles into PMMA based denture resins might enhance mechanical and surface related qualities as shown in previous studies (Gad & Abualsaud, 2019; Ghahremani et al., 2017). Furthermore, it has been demonstrated that adding titanium dioxide nanoparticles to 3D-printed dental resins improves mechanical properties, including flexural strength, flexural modulus, and heat stability. The use of TiO2 into 3D printed denture base resins led to a significant decrease in Candida albicans growth, indicating a better biological performance. But high nanoparticle loading may lead to particle agglomeration and negatively affect printability and material homogeneity, highlighting the importance of optimizing filler concentration and processing parameters (Chen et al., 2019; Mubarak et al., 2020; Altarazi et al., 2024).

**Aluminum oxide ($Al_2O_3$) nanoparticles**

To obtain parts with enhanced mechanical and functional properties, suitable for complex and specialized geometries, UV-curable resin and $Al_2O_3$ nanoparticles are used. The addition of $Al_2O_3$ nanoparticles to the UV resin improved the crack resistance, surface hardness and wear resistance of the UV resin. The modifications are as a result of intrinsic characteristics of small size of

DOI: 10.32828/mdj.v22i1.1261

the nanoparticles and large surface area, which permits a more consistent distribution of stress and enhances energy absorption under applied pressure (Al-helli et al., 2025). Aluminum oxide ($Al_2O_3$) nanoparticles can be used in a UV curable resin for 3D printing, and while this has mechanical advantages, there are also a number of drawbacks. At high filler loadings (>10 wt.%) problems with printability were observed. Weak adherence of the layers, particle sedimentation, and higher viscosity prevented the smooth flow of resin. At very high concentrations (e.g., 30 wt.%), printing failures occurred and overall dimensional accuracy decreased, indicating that optimization of filler content and processing conditions is critical to maintain quality in 3D-printed components (Al-helli et al., 2025).

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**Table 1:** Summary of literature review

| Type of resin | Type of nanofillers | Tests | Results | Ref. |
|---|---|---|---|---|
| 3D Printed denture resin | Porosphere / ZnO nanoparticles | Compressive strength | Improved compressive strength | Priya et al., 2023 |
| 3D Printed PMMA composite | Titanium Dioxide ($TiO_2$) nanoparticles | Surface cracks, cytotoxicity, antibacterial activity | Enhance both mechanical and antibacterial properties | Chen et al., 2019 |
| 3D-printed resin | Titanium Dioxide ($TiO_2$) nanoparticles | Mechanical and thermal properties | Significantly improved heat stability and conductivity | Al-helli et al., 2025 |
| 3D-printed resin | Silicon dioxide ($SiO_2$) nanoparticles. | Flexural strength, impact strength, surface and hardness | Flexural strength, impact strength, and hardness | Gad et al., 2022 |
| 3D-printed resin material | Titanium Dioxide ($TiO_2$) nanoparticles | Antifungal characteristics | Improved antifungal effect against Candida albicans. | Altarazi et al., 2023 |
| 3D-printed resins | Zirconium dioxide (ZrO2) nanoparticles | Surface roughness and antibiofilm action | Significant decrease in the *C. albicans* count, and adding small amounts of $ZrO_2$ did not change the roughness of the surface. | Khattar et al., 2023 |
| 3D printing resins | Zirconium dioxide nanoparticles ($ZrO_2$) and silicon dioxide nanoparticles ($SiO_2$) | Flexural strength (FS) | Substantial improvement in the flexural strength | AlGhamdi et al., 2025 |
| 3D printing resin | Aluminum oxide nanoparticles | Compressive strength, microhardn ess, and wear rate | Substantially improved the material's fracture resistance, improved its microhardness, and minimized the wear rate | Altarazi et al., 2023 |

DOI: 10.32828/mdj.v22i1.1261

## Mechanisms of Reinforcement in 3D Printed photopolymers by Nanofillers

### Filling of Microvoids and Defects

During the 3D-printing procedure of resin, tiny voids and pores may develop inside it. These micro-gaps are filled by addition of nanofillers like SiO2, TiO2, ZrO2 or Al2O3 nanoparticles. This improves the mechanical density and strength of the materials by reducing structural flaws and increasing its internal uniformity (Robakowska et al., 2023; AlGhamdi et al., 2025).

### Crack Inhibition

Under mechanical stress (e.g., flexure, tensile load, or impact), microcracks may develop at stress concentration locations within the polymer matrix. Cracks are connected using nanofillers. By increasing the energy required for fractures to propagate, they become more resistant to breaking. This technique performs as long as the nanofillers are evenly distributed and surface functionalized (Xue et al., 2025; Noworyta et al., 2023). Previous studies have demonstrated that reinforcing 3D-printed denture base resins with $ZrO_2$ nanoparticles can enhance multiple mechanical properties simultaneously. Al-Sammraaie et al. (2024) reported a significant positive correlation between tensile strength and diametral compression strength, indicating improved stress distribution and crack resistance following nanoparticle incorporation.

### Enhanced Photopolymerization Efficiency

Some nanofillers, such as $TiO_2$ and $SiO_2$, modify local light propagation inside vat photopolymer resins by scattering and redistributing the incident radiation. At appropriate particle sizes and loadings, this scattering can brighten shadowed regions and promote more uniform photoinitiator activation across the cured volume, resulting in an increased and more homogeneous degree of conversion and therefore more consistent mechanical properties between and within layers. However, excessive scattering or absorption (e.g., from large, highly absorbing, or aggregated particles) reduces penetration depth and harms cure depth; hence, an optimal balance of particle size, concentration, and refractive-index matching is essential (Robakowska et al., 2023; Mubarak et al., 2020).

## Synthesis Methods of Nanoparticles

### A- chemical method

### Sol-Gel method

The sol-gel method is one of the most straightforward methods for the production of nano- and microstructures of superior quality. This approach provides a variety of benefits over other synthesis routes, including being able to manage the texture, size, and surface properties of the materials; the possibility of producing materials with large surface areas; and the ease of implementation. It is also cost-effective and of good quality. The Sol-Gel technique is a technique that uses a colloidal solution (sol) to produce a network resembling gel with an aqueous and solid phase due to a number of chemical processes. The process can be summarized into five stages: hydrolysis, condensation, aging, dehydration and crystallization. The most used nanofillers are TiO2 and SiO2. converts elements into an emulsion that is later dried to produce fibers or nanoparticle (Navas et al., 2021; Baig et al., 2021).

DOI: 10.32828/mdj.v22i1.1261

**Precipitation (co-precipitation) method**

One of the simplest and least expensive procedures for the production of metal oxide nanofillers such as ZnO and ZrO2 is the precipitation or co-precipitation approach. The metal ions are dissolved in an aqueous or non-aqueous solution and precipitated out by addition of suitable base or precipitation agent. The resulting material is cleaned, dried and typically calcined to create pure and refined nanoparticles. Due to its reproducibility and scalability, this technique is particularly well-suited for the production of metal oxide nanofillers that are utilized in dental resin composites, as it enables precise control over particle composition and purity (Chandra et al., 2010).

**Hydrothermal (Solvothermal) Method**

This technique involves synthesizing nanoparticles in a sealed vessel (autoclave) under elevated temperature and pressure conditions (<100 °C, <1 atm). The regulated nucleation and development of crystals culminate in the formation of nanoparticles with well-defined forms and sizes (Nayak et al., 2023; Hayashi et al., 2010). The morphology of the product can be tuned to spheres, rods, fibers etc. by varying the reaction parameters such as time, temperature, pressure, solvent content.

Hydrothermal and solvothermal synthesis are especially beneficial for the synthesis of highly crystalline nanoparticles with a homogeneous particle size distribution and high purity, hence ideal for advanced dental applications and biomaterials (Hayashi & Hakuta, 2010).

**Electrospinning Method**

Electrospinning is the technology for fabrication of nanofibers, especially those composed of titanium dioxide ($TiO_2$) and polymers. A polymeric or metal-based fluid is expelled under a high-voltage electric field to produce continuous nanofibers. This process facilitates the generation of fibers characterized by a high aspect ratio, consistent morphology, and adjustable diameter, rendering it optimal for biomedical and dental applications (Venmathi et al., 2024; Sheikh et al., 2010).

**B- Physical Method**

**High-Energy Ball Milling**

The procedure consists of mechanical grinding of metallic or ceramic materials for producing nano-scale particles. It is simple, straightforward and applicable for inorganic particles (Altaf et al., 2020).

**Vapor Deposition (PVD / CVD)**

This method uses vapor to create thin films or nanoparticles on appropriate surfaces. provides outstanding control over the size, content, and cleanliness of the particles. Extensively employed for nanostructures and high-precision coatings (Mayeen et al., 2018).

**Drawbacks of incorporating nanofillers into Vat 3D Printing process**

Although the incorporation of nanofillers into 3D-printed resins can significantly enhance mechanical, thermal, and biological properties, there are several drawbacks and challenges that have been reported, as shown in Table 2.

**Table 2:** Major drawbacks of Using nanofillers in the process of Vat 3D printing

DOI: 10.32828/mdj.v22i1.1261

| Drawbacks | Description | Ref. |
|---|---|---|
| Increased resin viscosity | The incorporation of nanofillers (such as $SiO_2$, $ZrO_2$, and $TiO_2$) might lead to an increased viscosity of the resin, which is crucial for printability, rendering it difficult to stabilize and circulate within the tank, thus resulting in inaccuracies. | Korčušková et al., 2025; Fatalla et al., 2020; Priya et al., 2023; Zaharia et al., 2017 |
| Nanoparticle agglomeration | Nanoparticles have a tendency to aggregate, nanoparticles can induce surface defects, and the resin became inhomogeneous with microcracks. | Gad et al. 2022; 2020; Mayeen et al., 2018; Korčušková et al., 2025 |
| Interference with photopolymerization | Specific nanoparticles induce partially cured layers by reflecting or absorbing UV light, hence diminishing the efficacy of photopolymerization. | Jordan et al., 2005; Majeed et al., 2024; Majeed., 2024; Korčušková et al., 2025 |
| Localized layer defects | High concentration or uneven distribution of nanoparticles may result in local mechanical weaknesses and defects in the printed layers. | Wang et al., 2020; Viswambharan et al., 2020; Mayeen et al., 2018; Korčušková et al., 2025 |

**Limitations of the study**

This review shows that there is a lack of any long-term clinical studies on 3D-printed materials that are reinforced with nanofillers. Most of the studies were done in vitro, focusing on their mechanical, surface, and antimicrobial properties. This makes it harder to figure out how well they will work in real-life clinical situations. It is also hard to apply the results to other situations because the nanofillers, particle sizes, ratios, and printing methods are all different. However, our knowledge on the modifications of long-term biocompatibility, cytotoxicity and intraoral behavior after nanofiller addition is still limited. It's difficult to say if these reinforced resins are always superior than normal 3D printed materials for dental purposes.

**Conclusion**

In conclusion, the inclusion of nanofillers in 3D printed dental resins leads to significant enhancements in their mechanical, thermal, and surface properties. Various nanoparticles such as ZrO 2, SiO 2, TiO 2 and ZnO have shown enhancement in flexural strength, hardness, toughness and sometimes antibacterial characteristics. Dimensional stability and printing accuracy for stereolithography and other 3D printing technologies are also improved by nanofillers.

**Conflict of interest**

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

DOI: 10.32828/mdj.v22i1.1261

**Acknowledgments**

The University of Baghdad (www.uobaghdad.edu.iq) is acknowledged by the writers for its assistance with this work.

**Deceleration of conflicting interests**

Regarding the research, authorship, and/or publication of this paper, the authors disclosed no potential conflicts of interest.

**Funding:** This study is part of MSc project and is partially self-funded.

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