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NANOCOMPOSITES IN DENTISTRY– A REVIEW

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ABSTRACT Advances in nanotechnology have led to significant improvements in resin-based restorative materials used in operative dentistry. Nanocomposite resins are characterized by the presence of filler particles in the nanometer range, which enable enhanced filler loading and improved interaction between the resin matrix and fillers. These modifications result in superior mechanical performance, improved surface characteristics, and enhanced optical behaviour when compared with conventional composite materials. The review is to critically discuss the scientific basis and clinical relevance of nanocomposite resin restorations, including their formulation, classification, physical and mechanical properties, polymerization characteristics, handling behaviour, and long-term clinical performance. Emerging innovations such as bioactive fillers, antibacterial nanoparticles, and smart composite systems are also explored. By summarizing current evidence, this review aims to assist clinicians in understanding the clinical potential and limitations of nanocomposite resins and in selecting appropriate restorative materials for different clinical situations.

KEYWORDS :

INTRODUCTION

Resin-based composite materials are widely used in restorative dentistry because of their esthetic potential, adhesive bonding capability, and conservative approach to cavity preparation. Continuous improvements in composite resin formulation have significantly enhanced their clinical performance and longevity over time[1]

Early composite resin systems were associated with several limitations, including inadequate wear resistance, surface roughness, marginal degradation, and compromised long-term esthetic outcomes, which restricted their clinical success[2]

The application of nanotechnology in restorative dentistry led to the development of nanocomposite resins, which were specifically designed to overcome the shortcomings of earlier composite materials by improving mechanical properties, surface characteristics, and clinical durability[3]

Evolution of Resin-Based Composite Materials

The evolution of resin-based composite materials has progressed from macrofilled to microfilled, hybrid, and microhybrid composites. While macrofilled composites demonstrated acceptable strength, they showed poor polishability and excessive wear. Microfilled composites improved surface smoothness but exhibited inferior mechanical properties due to reduced filler loading.[4]

Hybrid and microhybrid composites attempted to combine strength and esthetics; however, long-term clinical issues such as filler plucking and surface degradation remained evident, particularly in stress-bearing restorations.[2]

Nanocomposite resins represent a major advancement in composite technology by incorporating nanosized filler particles, resulting in improved wear resistance, polish retention, and overall clinical performance.[3]

Classification of Nanocomposite Resins

Nanocomposite resins are resin-based composites containing filler particles in the nanometer range (1–100 nm).[2] Based on filler distribution, they are classified into nanofilled, nanohybrid and nanocluster composites.[9]

Nanofilled Composites

These contain discrete nanoparticles (1–100 nm) uniformly distributed within the resin matrix. They offer excellent polishability and esthetics.[10]

Nanohybrid Composites

These contain a combination of nano-sized and conventional filler particles. They provide a balance between strength and polishability.[10]

Nanocluster Composites

These consist of clusters of nanoparticles that act as larger filler particles while maintaining nanoscale benefits.[10]

Composition of Nanocomposite Resins

Resin Matrix

The organic matrix of dental composites was developed to overcome early challenges like poor curing and color instability. In the late 1950s, Bowen introduced Bis-GMA (from bisphenol A and glycidyl methacrylate), which became the standard resin matrix due to its ability to cure at room temperature with low polymerization shrinkage (~5%) and good overall properties.[11]

Bis-GMA has a high molecular weight, giving strength but also making it highly viscous and difficult to handle. To improve its flow and workability, it is diluted with low-viscosity monomers like TEGDMA (commonly ~25%). However, some monomers like methyl methacrylate are not preferred due to higher shrinkage and volatility.

The organic matrix also contains other essential components such as polymerization inhibitors, catalysts, tertiary amines, UV activators, and UV absorbers, which help control setting and stability.

Another commonly used resin is urethane dimethacrylate (UDMA), which lacks aromatic rings. It serves a similar role as Bis-GMA but offers lower polymerization shrinkage, although it still has relatively high viscosity.

Filler Particles

Inorganic fillers are incorporated into dental resin composites to enhance their mechanical and physical properties. They increase stiffness and surface hardness, reduce polymerization shrinkage, and help achieve a lower coefficient of thermal expansion—especially when a higher proportion of stable filler particles is used compared to the resin matrix.[11]

Over time, the development of composite resins has focused on reducing filler particle size to improve polishability and aesthetics. Early macrofill composites (10–50 µm) had poor surface finish and appearance. This led to the introduction of microfill, hybrid, microhybrid, nanofill, and nanohybrid composites, each with progressively smaller and more refined particle sizes. These advancements improved both the mechanical properties and esthetic outcomes.

However, there is often overlap in particle size distribution, making it difficult to clearly distinguish between microhybrid and nanohybrid composites, as both contain a combination of micro- and nanoparticles.

Coupling Agents

Silane coupling agents chemically bond filler particles to the resin matrix, improving stress transfer and resistance to hydrolytic degradation. Effective silanization is essential for long-term durability.[13]

Initiator Systems

Photoinitiatores in curing systems have enhanced depth of cure and color stability in nanoco systems, primarily camphorquinone-based, initiate polymerization upon light activation. Advanc mposites.[14]

Physical and Mechanical Properties

Nanofilled resin composites demonstrate enhanced mechanical and physical properties primarily due to the incorporation of nanosized filler particles and improved filler–matrix interaction.

Mechanical properties:

Nanocomposites exhibit high flexural strength, compressive strength, and fracture toughness, making them suitable for both anterior and posterior restorations. Their mechanical performance is generally comparable to or slightly better than hybrid composites. The presence of nanoclusters improves stress distribution within the material, thereby enhancing resistance to fracture.[1]

They also show excellent wear resistance, which is attributed to the small particle size and uniform filler distribution, reducing filler particle loss during function. Additionally, nanocomposites possess adequate surface hardness, contributing to their resistance against occlusal wear and abrasion.

Physical properties:

Nanocomposites have reduced polymerization shrinkage due to higher filler loading, which helps in maintaining marginal integrity and reducing microleakage. Their coefficient of thermal expansion is closer to that of tooth structure, improving dimensional stability under thermal changes.[1]

A key advantage is their superior polishability and gloss retention, resulting from nanosized fillers that produce a smoother surface. This also leads to lower surface roughness, minimizing plaque accumulation and staining.

Water sorption and solubility are generally within acceptable clinical limits, although these properties depend on the type of resin matrix used. Overall, nanocomposites exhibit improved optical properties, including better translucency and esthetics.

Optical and Esthetic Properties

Nanocomposites exhibit superior optical and esthetic properties due to the incorporation of nanosized filler particles and improved filler–resin interaction. The extremely small particle size (in nanometer range) significantly influences how light interacts with the material.

Optical properties:

Nanocomposites demonstrate enhanced translucency and light transmission, closely resembling natural enamel. This is primarily due to reduced light scattering, as the nanosized fillers are smaller than the wavelength of visible light. Additionally, better refractive index matching between filler particles and resin matrix further improves optical uniformity.

These materials also exhibit improved color blending ability (chameleon effect), allowing restorations to adapt to surrounding tooth structure. This results in more natural-looking restorations with minimal shade mismatch.

Esthetic properties:

One of the major advantages of nanocomposites is their excellent polishability and long-term gloss retention. The small particle size allows for a smoother surface after finishing and polishing, which enhances esthetics and reduces plaque accumulation.

Nanocomposites also show low surface roughness, which contributes to better stain resistance and color stability over time. Unlike larger particle composites, they resist surface degradation and maintain their shine for longer periods.

Furthermore, the improved surface characteristics lead to enhanced wear resistance, which helps preserve the esthetic appearance even under functional stress[5]

Polymerization Shrinkage and Marginal Integrity

Polymerization shrinkage in resin composites occurs due to the conversion of monomer molecules into a cross-linked polymer network, leading to volumetric contraction. In nanocomposites, this shrinkage is influenced by the filler content, resin composition, and curing conditions.[16]

An increase in nanofiller loading reduces the amount of resin matrix, thereby decreasing overall polymerization shrinkage. However, shrinkage alone is not the only concern—polymerization shrinkage stress is more clinically significant. This stress develops when the composite is bonded to cavity walls and cannot freely contract during curing.

The study emphasizes that shrinkage stress depends not only on the amount of shrinkage but also on the elastic modulus and polymerization rate. Materials with a higher modulus generate greater stress, even if shrinkage is relatively low.

Shrinkage stress can lead to:

- Marginal gap formation
- Debonding at the tooth–restoration interface
- Microleakage and postoperative sensitivity

Nanocomposites, due to their optimized filler distribution and improved formulation, can exhibit better control over shrinkage, but proper clinical techniques (incremental placement, controlled curing) are essential to minimize stress and maintain marginal integrity.

Handling Characteristics and Clinical Application

Nanocomposites exhibit improved handling properties due to the incorporation of nanosized fillers and optimized resin matrices[1]

- They have improved consistency and flow, allowing easier placement and adaptation to cavity walls
- Reduced filler particle size results in better sculptability and carving ability
- Nanocomposites demonstrate non-sticky handling, facilitating manipulation during restorative procedures
- Their excellent polishability and smooth surface finish enhance finishing and polishing procedures
- Improved filler distribution provides better marginal adaptation, reducing void formation Additionally, the increased filler loading reduces resin content, which contributes to controlled viscosity and improved workability

Clinical Applications[11]
Nanocomposites are widely used in various fields of dentistry due to their superior properties:

1. Restorative Dentistry
- Used for anterior and posterior restorations
- Provide excellent esthetics and wear resistance
- Suitable for Class I, II, III, IV, and V restorations

2. Preventive Dentistry
- Nanoparticles (e.g., silver, zinc oxide) provide antibacterial properties, reducing secondary caries

3. Adhesive Systems
- Used in bonding agents to improve penetration and bond strength

4. Endodontics
- Used in sealers and restorative materials with improved sealing ability

5. Implant Dentistry
- Nanocomposite coatings enhance osseointegration and antimicrobial activity

6. Prosthodontics
- Used in denture bases and prosthetic restorations for improved durability

Clinical Performance of Nanocomposite Restorations
Nanocomposites have shown excellent clinical performance due to their improved mechanical, physical, and esthetic properties.

Clinical studies and systematic reviews indicate that nanocomposites exhibit high survival rates and long-term durability, comparable to or better than conventional hybrid composites. They demonstrate good retention, minimal wear, and resistance to fracture, making them suitable for both anterior and posterior restorations.[17]

One of the key advantages is their superior marginal integrity, with reduced marginal discoloration and microleakage over time. This is attributed to their lower polymerization shrinkage and improved filler distribution.

Nanocomposites also provide excellent esthetic outcomes, including long-term gloss retention, smooth surface texture, and color stability. Clinical trials have reported low incidence of secondary caries and postoperative sensitivity.

Long-term studies (up to 7 years) have confirmed that nanocomposites maintain functional and esthetic stability, with performance comparable to or exceeding traditional composite materials.[18]

Recent Advances in Nanocomposite Technology
Multifunctional Nanocomposites
Modern nanocomposites are no longer passive materials; instead, they are designed to be multifunctional by combining mechanical strength with biological activity. These materials exhibit improved wear resistance, enhanced polish retention, and reduced polymerization shrinkage, which together contribute to better long-term clinical performance. In addition, the incorporation of bioactive fillers such as hydroxyapatite enables these composites to mimic natural tooth structure and improve integration with surrounding dental tissues.[21]

Incorporation of Novel Nanoparticles
Recent research has focused on the incorporation of advanced nanoparticles such as silver, zinc oxide, graphene oxide, and titanium dioxide into dental composites. These nanoparticles significantly enhance mechanical properties, including flexural strength and fracture toughness. Furthermore, they impart antibacterial properties, thereby improving the material's resistance to microbial colonization.[22] Silver nanoparticles, in particular, demonstrate strong antimicrobial activity by releasing ions that disrupt bacterial cell membranes and metabolic pathways.

Antibacterial and Bioactive Nanocomposites
A major advancement in nanocomposite technology is the development of antibacterial materials that actively reduce biofilm formation and the risk of secondary caries. These nanocomposites inhibit bacterial adhesion, disrupt microbial cell membranes, and prevent plaque accumulation on the restoration surface. Additionally, bioactive nanocomposites are capable of releasing calcium and phosphate ions, which promote remineralization of enamel and dentin, thereby aiding in tooth repair and regeneration.

Self-Healing and Smart Materials
Recent innovations have led to the development of self-healing nanocomposites, which possess the ability to repair microcracks within the material, thereby enhancing the longevity of restorations. These materials contain microcapsules or healing agents that are released when cracks form, allowing the material to restore its structural integrity. Moreover, smart nanocomposites have been developed to respond to environmental stimuli such as changes in pH, temperature, or bacterial activity, enabling targeted therapeutic action and improving clinical outcomes.

Improved Mechanical and Physical Properties
Advances in filler technology and nanoparticle incorporation have resulted in significant improvements in the mechanical and physical properties of nanocomposites. These materials exhibit increased flexural strength, enhanced fracture resistance, reduced polymerization shrinkage, and improved thermal stability. Additionally, their dimensional accuracy is improved, which contributes to better clinical performance and longevity.[23]

Enhanced Optical and Esthetic Properties
Nanocomposites now demonstrate superior optical and esthetic properties compared to conventional composites. They exhibit improved translucency and light transmission, which closely mimic natural tooth structure. Furthermore, they provide excellent polishability, long-term gloss retention, and enhanced color stability. These properties are attributed to nanosized fillers that reduce light scattering and produce a smoother surface.[24]

Integration with Digital Dentistry
Recent advancements have also enabled the integration of nanocomposites with digital dentistry technologies such as CAD/CAM systems and 3D printing. This allows for the fabrication of highly precise and customized restorations with optimized material properties, thereby improving clinical efficiency and patient outcomes.

Limitations of Nanocomposites
Nanocomposites, despite their advantages, have certain limitations. Polymerization shrinkage and shrinkage stress can lead to marginal gaps, microleakage, and postoperative sensitivity. They are also technique-sensitive, requiring proper placement and curing to achieve optimal results.

Some formulations exhibit handling difficulties due to high viscosity, while long-term water sorption and degradation may affect durability and color stability. Although wear resistance is good, they may not always outperform hybrid composites in high-stress areas.

Additionally, concerns exist regarding nanoparticle toxicity, higher cost, and limited long-term clinical evidence compared to conventional materials.

Future Perspectives
Future advancements aim to improve bioactivity, antibacterial efficacy, and long-term durability of nanocomposites through innovations in filler technology and resin formulations. Continued research is expected to further enhance their clinical performance. Despite these advancements, certain challenges remain, including concerns regarding nanotoxicity, limited long-term clinical data, and higher costs associated with advanced materials. Future research is focused on developing safer and more biocompatible nanomaterials, enhancing self-healing and regenerative capabilities, and expanding their applications in regenerative dentistry and tissue engineering.

CONCLUSION
Nanocomposites represent a significant advancement in restorative dental materials, combining improved mechanical strength, enhanced esthetic properties, and better clinical performance compared to conventional composites. The incorporation of nanosized fillers has led to superior polishability, wear resistance, reduced polymerization shrinkage, and improved marginal integrity, making them highly suitable for both anterior and posterior restorations.

Recent developments have further expanded their potential through the introduction of bioactive, antibacterial, and smart nanocomposites, which not only restore but also actively contribute to the maintenance of oral health. Despite these advantages, certain limitations such as technique sensitivity, shrinkage stress, cost, and the need for long-term clinical evidence remain areas of concern.

Overall, nanocomposites have become an integral part of modern dentistry, and with ongoing research and technological advancements, they are expected to evolve into more durable, biocompatible, and multifunctional materials, shaping the future of restorative and preventive dental care.

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