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A Comprehensive Review on the Role of Hexagonal Boron Nitride and Mesoporous Silica Nanoparticles in Enhancing Dental Composites

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ABSTRACT

The integration of mesoporous silica nanoparticles (MSN) and hexagonal boron nitride (HBN) as fillers in dental composites represents a promising advancement in restorative dentistry. These nanofillers address several limitations of traditional composites, such as microbial infiltration, inadequate mechanical performance, and poor resistance to thermal and mechanical stress. HBN contributes exceptional thermal conductivity, chemical stability, and mechanical strength, while MSN provides a high surface area that enhances filler dispersion and promotes antimicrobial activity (Niu et al., 2020; Wang et al., 2020).

This review critically examines the impact of incorporating HBN and MSN into dental composites, particularly in terms of morphological characteristics, mechanical reinforcement, thermal resistance, and antimicrobial efficacy. The study by KaptanUsul et al. (2024) provides a detailed evaluation of composites formulated with 5% and 10% filler loadings of HBN and MSN in a Bis-GMA/TEGDMA matrix. Advanced analytical methods such as FTIR, EDS, SEM, X-ray interferometry, and thermogravimetric analysis demonstrated improved structural bonding and thermal stability (Silverstein et al., 2021; Cullity& Stock, 2021).

Antimicrobial assays revealed significant inhibitory effects against Staphylococcus aureus, Escherichia coli, and Saccharomyces cerevisiae, with minimum inhibitory concentrations ranging from 1–5 mg/mL(Mohammed et al., 2020; Zhou et al., 2020). Despite these positive outcomes, challenges remain, particularly regarding long-term performance, tribological testing, and comprehensive biocompatibility assessments. Additional research is needed to address issues related to large-scale manufacturing, wear resistance, and cytotoxicity. Ultimately, the incorporation of HBN and MSN has the potential to yield restorative materials that are mechanically durable, biologically active, and clinically resilient (Xu et al., 2021; Borges et al., 2019).

1. INTRODUCTION

1.1. The Evolution of Dental Composites:

In the Twentieth Century, there has been a drastic evolution to the form of dental composites as they were used towards the middle of that century. Economic cost and longevity of dental amalgam restorations meant they were the most widely used material by dentists. Nevertheless, the need to replace resin-based composites due to mercury toxicity and lack of appeal dictated their use. Although these materials were more appealing and biocompatible, they suffered from low toughness and were prone to shrinkage and contamination (Ferracane, 2022; Mitra et al., 2023).

1.1.1. The Early Stages of Composite Developments:

Initially, the dental composites achieved modernity with the use of an inorganic quartz or silica filler mixture along with a bisphenol A-glycidyl methacrylate (Bis-GMA) matrix and triethylene glycol dimethacrylate (TEGDMA) resin. While there was further enhancement of the aesthetic properties of dental composites, much more work was still needed regarding curing shrinkage. Researchers responded to this by developing hybrid composites that used plastic fillers to enhance mechanical strength. (Powers &Sakaguchi, 2021).

1.1.2. Difficulties Encountered in the Use of Traditional Composites:

Even though progress continues to be made, conventional composites are still faced with the following major difficulties:

- **Mechanical Degradation:** Dental composites are subject to wear, cracking, and chipping over time because of the repetitive loading forces during mastication (Alharbi et al., 2018; O'Brien, 2021).
- **Microbial Infiltration:** Within the cavity, composite materials interface with tooth structure, leading the cavity to be afflicted by the interface that allows the biofilm to accumulate and eventually results in secondary caries and affect the restoration.
- **Hydrolytic Instability:** Absorption of water means dental composites undergo hydrolytic degradation which leads to swelling that cracks and finally fails.
- **Thermal and Chemical Instability:** Substance dissolution in the oral cavity, with its changing temperature and pH, speeds up material destruction. (Alharbi et al., 2018; O'Brien, 2021).

To address the above issues, newer dental materials with high mechanical strength, resistance to microbes, and stability to the environment are required.

1.2 The Application Of Nanotechnology In Dentistry:

The integration of nanotechnology into dental materials composite technology has replaced the problems of traditional composite materials. The addition of some other new fillers like hexagonal boron nitride (HBN) nanoparticles and mesoporous silica MSN nanoparticles (HBN) has demonstrated improved mechanicals as well as antimicrobial properties (Niu et al., 2020; Mohammed et al., 2020).

1.2.1. Properties of Nanofillers:

Nanofillers are considered the most efficient elements that take care of functional enhancement of dental composites by improving the adhesion of the filler to the polymer matrix. Polymerization shrinkage is reduced, wear resistance is enhanced, and optical properties are improved. With these two features, HBN and MSN are exceptionally good candidates:

Hexagonal Boron Nitride (HBN): Like graphene, HBN has a layered crystalline structure. Its thermal conductivity is higher, and it is more chemically stable and mechanically stronger. Apart from these properties, its HBN's natural lubricating features, owing to its wear resistance, make it appropriate for use at high mechanical loads, like in dental restoration. (Wang et al., 2020).

Mesoporous Silica Nanoparticles (MSN): MSN exhibits exceptionally high surface areas, is porous, and is biocompatible. These features guarantee adequate dispersion in the composite matrix and enable the incorporation of antibacterial substances that help in the control of biofilms and bacterial growth (Vallet-Regi et al., 2020).

Mechanical Performance and Load-Bearing Capacity: The composite's mechanical properties improved significantly with the use of nanotechnology (in comparison to their components) (Xu et al., 2021). Studies show that HBN increases compressive strength, while MSN is efficacious for crack resistance and wear resistance (Borges et al., 2019; Sharma et al. 2021).

1.2.2. Advantages of Nanotechnology in Dental Materials:

The application of nanotechnology in dental composites has a number of obvious advantages.

Advanced Mechanical Properties: Added nanofillers in a dental composite result to an increase in compressive strength, elastic modulus, and even fracture toughness because they minimize stress concentrations and crack propagation.

Improved Aesthetics: As a result of enhanced optical properties, composites can replicate the natural translucency of enamel due to the submicroscopic size of nanofillers.

Antimicrobial Activity: The use of MSN incorporated antimicrobial agents nanofillers is said to decrease bacterial colonization and biofilm formation.

Long-Term Durability: The extended life span of restorations is said to be better with the use of nanofillers due to their enhancing effect on thermal, chemical, and hydrolytic stability (Xu et al., 2021).

This makes dental construction more convenient and easier for the patients and dentists therefore saves time and money. These advantages underscore the transformative potential of nanotechnology-based dental composites.

1.3. Research Scope And Objectives:

Because of the very convincing use of nanofillers HBN and MSN, this review set out to fully analyze their effects on the structural, mechanical, thermal, and antimicrobial properties of dental composites. The focus of the analysis is on the systematic analysis done by KaptanUsul et al. (2024) that studied combination of HBN and MSN in a bis-gmategdma polymer matrix at different weight fractions 5 % and 10 %.

1.3.1. Major Areas of Concern in Research:

As with any review, a few key research questions have been set forth:

- Structural Integrity: In what ways do HBN and MSN affect the bonding, crystallinity, and dispersion relativities of the dental composites?
- Thermal Stability: How much do these nanofillers increase the thermal and glass transition temperatures of the dental composites?
- Mechanical Performance: In what way do HBN and MSN affect the compressive strength, elastic modulus and fracture toughness of the composites?
- Antimicrobial Efficacy: To what degree do the composites interact with the most aggressive oral biofilm pathogens and what level of biofilm resistance do the composites provide?
- Long Term Durability: How resistant are HBN- and MSN-based composites to hydrolytic degradation, chemical erosion and wear in the oral environment?

1.3.2. Research Scope and Objectives:

This review aims to evaluate the effects of incorporating hexagonal boron nitride (HBN) and mesoporous silica nanoparticles (MSN) into dental composites. It focuses on their influence on the composites' mechanical strength, thermal resistance, structural integrity, and antimicrobial efficacy. Emphasis is placed on the recent study by KaptanUsul et al. (2024), which analyzed HBN and MSN at 5% and 10% weight ratios in a Bis-GMA/TEGDMA matrix.

1.3.3 Key Research Questions

1. How do HBN and MSN impact bonding, crystallinity, and nanoparticle dispersion in the resin matrix?
2. What effects do they have on thermal properties, including thermal stability and glass transition temperature?
3. How do they influence compressive strength, fracture toughness, and overall mechanical performance?
4. To what extent do they exhibit antimicrobial activity against key oral pathogens?
5. What is their potential for long-term durability in clinical settings?

1.3.4 Objectives:

- **Analyze Structural Integration:** Investigate chemical bonding, filler dispersion, and composite morphology using FTIR and SEM-EDS.
- **Evaluate Mechanical Properties:** Measure compressive strength, fracture resistance, and elastic modulus of the composites.
- **Assess Thermal Behavior:** Determine thermal stability and glass transition temperatures via TGA and DSC analysis.
- **Examine Antimicrobial Performance:** Quantify inhibition against E. coli, S. aureus, and S. cerevisiae using MIC and related assays.
- **Identify Knowledge Gaps:** Highlight the need for tribological testing, cytotoxicity evaluation, and commercial scalability.
- **Propose Future Directions:** Recommend research on advanced filler functionalization, biocompatibility testing, and long-term clinical trials.

2. METHODOLOGICAL FRAMEWORK

This section outlines the methodology adopted for synthesizing and analyzing dental composites modified with hexagonal boron nitride (HBN) and mesoporous silica nanoparticles (MSN), based on the experimental procedures described by KaptanUsul et al. (2024), supplemented with standard protocols from contemporary materials science and dental research literature.

2.1. Composite Fabrication:

The experimental dental composites were prepared by integrating HBN and MSN at weight percentages of 5% and 10% respectively into a Bisphenol A-Glycidyl Methacrylate (Bis-GMA)/Triethylene Glycol Dimethacrylate (TEGDMA) matrix. The base monomers were mixed in a 70:30 ratio (Bis-GMA:TEGDMA) to ensure optimal viscosity and mechanical integrity (Xu et al., 2021).

Nanoparticles were first functionalized using 3-methacryloxypropyltrimethoxysilane (γ-MPS) to improve compatibility with the resin matrix and promote covalent bonding, following procedures by Kargozar & Mozafari (2018). The silanized fillers were ultrasonically dispersed in ethanol for 20 minutes to prevent agglomeration (Chung et al., 2023).

A high-shear mechanical stirrer was employed at 1000 rpm for 15 minutes to ensure homogenous dispersion, followed by vacuum desiccation to remove entrapped air bubbles (Lohbauer et al., 2022). The paste was then loaded into custom molds and subjected to photo-polymerization using a 1200 mW/cm² LED curing unit for 40 seconds, ensuring uniform curing and minimizing polymerization shrinkage (Ge et al., 2019).

2.2. Analytical Techniques:

2.2.1. Structural and Morphological Analysis:

Fourier Transform Infrared (FTIR) Spectroscopy: Used to detect chemical bonding between the nanofillers and the resin matrix, confirming successful integration of silanized HBN and MSN via characteristic peaks (Silverstein et al., 2021).

X-ray Diffraction (XRD): Conducted to assess the crystallinity and phase composition of the composites. HBN peaks at 26.8° (002 plane) and 41.7° (100 plane) confirmed the hexagonal structure, while the amorphous profile of MSN suggested structural flexibility (Cullity& Stock, 2021).

Scanning Electron Microscopy (SEM) with Energy-Dispersive X-ray Spectroscopy (EDS): Employed to visualize the microstructure and elemental distribution. SEM images confirmed uniform nanoparticle dispersion, and EDS spectra identified boron, nitrogen, and silicon, validating the dual-filler system (Goodhew et al., 2021).

2.2.2. Thermal Characterization:

Thermogravimetric Analysis (TGA): Evaluated thermal decomposition profiles. HBN-MSN composites showed remarkable thermal resistance with less than 1.5% weight loss at 1000 °C, indicating robust filler-matrix interactions (KaptanUsul et al., 2024).

Differential Scanning Calorimetry (DSC): Used to determine the glass transition temperature (Tg). DM10 samples with 10% HBN/MSN exhibited a Tg of 218°C, reflecting enhanced cross-link density and thermal stability (Lu et al., 2023; Colak et al., 2018).

2.2.3. Mechanical Testing:

Compressive Strength: Tested using a universal testing machine (ISO 9917-1 standard). DM5 samples (5% filler) achieved a peak compressive strength of 103.48 MPa, outperforming commercial benchmarks like Filtek Supreme Ultra (KaptanUsul et al., 2024).

Elastic Modulus and Fracture Toughness: Assessed using three-point bending and single-edge notched beam (SENB) tests. HBN increased stiffness, while MSN provided improved crack resistance due to its stress-dissipating morphology (Huang et al., 2022; Borges et al., 2019).

3. EXPERIMENTAL INSIGHTS

This part analyzes in detail the results of the experiments aiming at the structural, mechanical, thermal, and anti-microbial characteristics of the HBN and MSN modified dental composites. The clear morphological uniformity, mechanical integrity, chemical stability, and antimicrobial characteristics of the materials is explained by numerous advanced characterization techniques.

3.1 Morphological and Structural Integrity

3.1.1. Intermolecular Forces and Chemical Bonds:

An analysis of the Fourier transforms infrared highlights spectroscopy (FTIR) indicates that the structural characterization assures some degree of success with regard to the incorporation of the nanofillers. The distinct peaks at 1327cm^{-1} reported are due to B-N stretching vibrations from hexagonal boron nitride (HBN) confirming its chemical bonding within the Bis-GMA/TEGDMA polymer matrix. The other peaks appearing in the range of 1045-1100cm^{-1} were due to stretching vibrations of Silicate mesoporous particles (MSN) silica that showed the existence of silicate frameworks that are stable.

Because of this synergistic bonding a molecular network was formed which in turn greatly improved the rigidity as well as the chemical stability of the polymer matrix (KaptanUsul et al. 2024, Fig 1). The degree of polymerization for the nanofillers and the resin matrix provided a chemical bond that prevented interfacial debonding which is characteristic of most other dental composites.

3.1.2. Composition of The Crystallinity and Other Phases:

X ray diffraction (XRD) studies showed that the hexagonal crystalline configuration of HBN possessed characteristic sharp diffraction peaks at 26.8o (002 Plane) and 41.7o (100 Plane) which were previously identified. These peaks have sharpness, suggesting the existence of moderately ordered HBN crystallites. On the other side the dulling of intensity of the broad peaks indicate the predominating amorphous nature of the MSN This implies that MSN provides flexibility, which is mechanical, and HBN offers rigidity, which is structural (KaptanUsul et al 2024 Fig 2)

The hybrid structure effectively balanced mechanical strength with toughness, which is fundamental for load-stressed toothing restorable dentures. Dual-phase crystallinity was important in the improvement of resistance to cracking and the reduction of brittleness.

3.1.3. Microstructural Homogeneity:

SEM/EDX imaging convinced us that the polymeric matrix contained uniformly distributed nanoparticles. Some degree of nanofillers agglomeration was observed, demonstrating that the pre-polymerization mixing step worked properly. Elemental mapping confirmed the presence of boron, nitrogen, and silicon, proving that both nanofillers were incorporated successfully (KaptanUsul et al. 2024, Fig. 3).

The uniformly dispersed nanoparticles inhibited micro voids formation that can weaken composites by providing sites for fracture propagation. This morphologic homogeneity increased resistance to mechanical erosion and deterioration of the composites, which are otherwise likely to fail prematurely.

3.2. Thermal Stability And Degradation Resistance

Thermal Stability And Durability:

HBN and MSN nanofillers are well known for their high thermal conductivity and hence, can be used in load bearing tooth dentures without any reservations (Singh et al., 2023). Also, the thermal stability of MSN reduces the rate of polymer degradation while in oral cavity (Lu et al., 2023).

3.2.1. Indicators for Thermal Stability:

TGA confirmed that HBN-MSN composites exhibits superior thermal resistance. Even at aggressive temperatures near 1000 °C, the DM5 and DM10 composites suffered little weight loss (1.44%) when compared to traditional composites. The heightened weight resistance these composites exhibited was explained by HBN's hexagonal lattice structure and MSN's thermal barrier capabilities (KaptanUsul et all, 2024, Fig. 5).

Due to the inorganic makeup of these nanofillers, the composites are applicable for high temperature dental applications such as crowns and bridges as they do not experience thermal decomposition prematurely.

3.2.2. Glass Transition Temperature (Tg):

DSC analysis showed marked increase in glass transition temperature (Tg) of 218 °C for the DM10 composite suggesting strong polymer cross linking as a result of filler matrix bonding. Improved interfacial adhesion between the nanofillers and polymer matrix resulted in greater restriction of segmental chain movement increasing Tg (KaptanUsul et al., 2024, Fig 6).

The aforementioned composite also has enhanced structural integrity which enables it to withstand long term clinical applications which include exposure to fluctuating oral temperatures. The high Tg ensures that the polymer does not soften under functional stress.

3.3. Mechanical Properties And Load Capacity:

Composites' mechanical features are said to be significantly enhanced with the addition of nanotechnology (Xu et al., 2021). Research indicates that while HBN improves compressive strength, MSN aids in wear and rack resistance (Borges et al., 2019; Sharma et al., 2021).

3.3.1. Compressive Strength and Elastic Modulus:

The mechanical testing results highlighted a stunning increase in load-bearing capacity of composite materials. The DM5 composite recorded outstanding performance with a compressive strength of 103.48 MPa, which is higher than that of the commercial materials, such as Filtek Supreme Ultra. This enhancement was ascribed to the active nanoparticle agglomeration and the strong interfacial bond between the fillers and matrix materials (KaptanUsul et al., 2024, Fig. 8).

Due to the inherent rigid nature of HBN, the elastic modulus increased proportionately with the amount of HBN in the matrix. On the contrary, over 10 % HBN undermined the tensile strength due to the rigid-brittle phenomenon typical in highly filled composites.

3.3.2. Fracture Toughness and Resistance to Deformation:

The B1, B3 and B4 composites exhibited increased fracture toughness, which is a result of the crack-deflecting action associated with the layered structure of HBN. The nanosheets acted as mechanical barriers, absorbing energy and preventing crack movement. In addition, spherical particles of MSN eased the intimal stress concentration, and, thus, increased the mechanical strength (KaptanUsul et al., 2024, p. 2301)

These specific characteristics provide improved fracture toughness, enabling the use of posterior crowns and bridges for demanding restoration.

3.4. Antimicrobial Activity:

Biofilm Inhibition: The composites inhibited the growth of microbial colonization of biofilm forming pathogens like Escherichia coli, Staphylococcus aureus and Saccharomyces cerevisiae (Zhou et al., 2020).

Antimicrobial Efficacy: Incorporation of MSN into dental composites improves the biofilm resistance of the composite which is important in avoiding secondary caries (Mohammed et al., 2020). More recent works revealed astonishingly high efficiency against microbes like Escherichia coli and Staphylococcus aureus (Kim et al., 2022).

Table: Comparative Properties of HBN and MSN as Nanofillers in Dental Composites

Property	Hexagonal Boron Nitride (HBN)	Mesoporous Silica Nanoparticles (MSN)
Structural Form	Layered crystalline	Amorphous, porous
Thermal Conductivity	High	Moderate
Mechanical Strength	Excellent compressive and tensile resistance	Enhances crack and wear resistance
Surface Area	Moderate	Very high
Chemical Stability	High	High
Antimicrobial Incorporation	Not inherent, requires doping	Excellent carrier for antimicrobial agents

4. CRITICAL APPRAISAL AND PROSPECTIVE DIRECTIONS

4.1. Methodological Strengths:

4.1.1. Comprehensive Analytical Framework:

Integration of advanced characterization such as Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscope with energy disperse spectroscopy (SEM-EDS), thermogravimetric analysis (TGA), and differential thermal analysis (DSC) into a single study reflects multi-modality approach. This approach adds relevance to the biological, structural, thermal, and mechanical aspects of the composite and simultaneously enhances the reliability of the observations through bias reduction (KaptanUsul et al., 2024, p. 2297).

4.1.2. Enhanced Nanofiller Incorporation:

The tactical strategy of simultaneously introducing HBN and MSN greatly enhanced the performance of the composites. HBN’s hexagonally crystalline material provided mechanical strength as well as thermal conductivity. At the same time, MSN's high surface area and porosity allowed for greater filler dispersion and improved antimicrobial effect. These single synergistic fillers properly met the challenges presented by conventional systems utilizing single filler (KaptanUsul et al., 2024, p. 2301).

4.1.3. Validation of Testing Procedures for Antimicrobial Life Activity:

The composite was tested for antimicrobial activity using traditional microbiological methods like Minimum Inhibitory Concentration (MIC), Minimum Bactericidal Concentration (MBC), and Minimum Fungicidal Concentration (MFC) assay analysis. The results indicate that the composites demonstrated wide range bioactive toxicity against microorganisms like Escherichia coli, Staphylococcus aureus, and Saccharomyces cerevisiae with an MIC range of 1-5 mg/ml.This superior bioactivity demonstrates the efficacy of the materials in the management of biofilm and non-primary dental infections (KaptanUsul et al., 2024, Table 4).

4.1.4. Optimization of Mechanical Properties:

The results of the mechanical testing provided clear proof of enhanced load bearing and durability capabilities. The DM5 composite outperformed commercial dental composites such as Filtek Supreme Ultra by having a compressive strength of 103.48 MPa. This was due to optimum nanofiller spacing which was above a sufficient level to prevent cavity creation and stress concentration areas within the matrix (KaptanUsul et al., 2024, Fig. 8).

4.1.5. Compositional Analysis of Structural Integrity and Thermal Stability:

The composites also showed the best thermal stability with the lowest weight loss and the highest glass transition temperatures (Tg). The use of MSN infused greater thermal resistance due to improved filler-matrix interlocking along with strong resistance to thermal decomposition. The DM10 composite, which had a maximum Tg of 218 degrees Celsius, demonstrates its claim towards the development of high-performance dental restorations (KaptanUsul et al., 2024, Fig. 6).

Table: Summary of Experimental Findings in HBN-MSN Composite Analysis (KaptanUsul et al., 2024)

Parameter	**Observation**
Compressive Strength (DM5)	103.48 MPa
Thermal Stability (TGA)	Minimal weight loss (1.44%) up to 1000 °C
Glass Transition Temperature (Tg)	218 °C for DM10 composite
Antimicrobial Efficacy (MIC)	Active against E. coli, S. aureus, S. cerevisiae (1–5 mg/mL)
Morphological Uniformity	Homogeneous nanoparticle distribution confirmed via SEM-EDS

4.2. Identified Limitations

4.2.1. Lack of Triobological and Wear Resistance Testing:

The absence of triobological testing is arguably the toughest limitation including wear resistance, surface roughness, and friction coefficient measurement. Since dental composites undergo constant abrasive actions from mastication and scrubbing with toothbrushes, implementing wear testing with known protocols such as three-body abrasion and sliding wear tests would help the study.

4.2.2. Data Gaps for Long-Term Stability and Aging:

Even though it was noted that water sorption and thermal stability was evaluated, the study was lacking in long term environmental durability measures like hydrolytic degradation, thermal cycling, and chemical aging in differing pH levels. These tests are fundamental to estimating the durability of the composites and clinically relevant reliability in the dynamic oral environment.

4.2.3. Gaps in Biocompatibility and Cytotoxicity:

One of the glaring oversights is the lack of in vitro cytotoxicity and biocompatibility testing with human cell lines like gingival fibroblasts, osteoblasts, and epithelial cells. Moreover, ISO 10993 biocompatibility evaluations with laboratory animals would validate the safety of the composites for extended clinical use.

4.2.4. Comparison with Other Commercial Composites:

Even with the composites' favorable outcomes, they were not evaluated alongside other commercially used dental materials like Tetric EvoCeram, Filtek Supreme Ultra, and Herculite Ultra. A benchmarking study would set the materials against their commercial counterparts in order to assess and identify competitive advantages and limitations.

4.2.5. Lack of Insights for Scalable Manufacturing:

This particular study did not look into the possibilities of bulk production including the availability of raw materials, cost efficient synthesis, and scalability of production. Considerations such as automated nanofiller synthesis and continuous-flow polymerization are necessary to expand from laboratory-scale results to commercially viable products (Ratner et al., 2023).

4.2.6. Missing Adhesion and bond Strength Test:

The current examination did not test the adhesive bonding strength of the composites with the enamel and dentin. Some standard adhesion tests, for example, shear bond strength and micro tensile bond strength measurements, would confirm their usefulness in performing dental restorations such as cavity fillings, veneers, and crowns.

4.2.7. Future Directions:

Research should shift focus toward the optimization of biocompatibility assessment to validate materials for clinical use (Bhatia et. al, 2021; Perez et. al, 2019). Comparative benchmarking with commercial products will also ensure competitive viability (Smith et al., 2021).

4.3. Prospective Directions

4.3.1. Triobological and Wear Resistance Testing:

The friction and wear resistance of the materials and their surface roughness together with pH will be measured integrating testing procedures such as ASTM G99. These evaluations would determine the material's durability over time, particularly with the aid bearing restorations.(Palaniappan et al., 2020).

4.3.2. Comprehensive Bio stability and Aging Studies:

Composites should undergo environmental stability tests like pH cycling, thermomechanical fatigue, hydrolytic degradation, and sorption, as well as solubility in compliance with ISO 4049 standards. The tests would give a practical estimate of the composites' stability over time within the oral environment.

4.3.3. Assessment of Cytotoxicity and Compatibility:

Gingival fibroblasts, dental pulp stem cells, and human osteoblasts require extensive in vitro biocompatibility testing. It is also imperative to comply with ISO 10993 and American Dental Association (ADA) compatibility standards prior to commencement of clinical trials.

4.3.4. Functionalization of Advanced Nanoparticles:

The incorporation of silver nanoparticles, zinc oxide, or hydroxyapatite in the filler matrix would expand tissue integrating capabilities and also enhance antimicrobial and osteoconductive properties. Core-shell nanofillers are expected to augment multifunctional properties even more.

4.3.5. Testing of Composite Adhesion and Bond Strength:

Composites' adhesive properties must be verified by means of adhesion tests of shear and micro-tensile bond strength evaluation. The results will determine their application in cavity restorations, crowns, and veneers.

4.3.6. Studies of Commercial Scale-Up:

Nanofiller automated synthesis, continuous flow photo polymerization, and large scale extrusion are methods that require further investigation for automation. Evaluating production costs, environmental sustainability, and quality control protocol would enable commercialization.

4.3.7. Field Trials and Patient Outcome Studies:

The controlled trials randomization with thorough patient outcome data collection over time should be conducted. Evaluations need to include longevity of restorations, resistance to bacterial colonization, and patient overall satisfaction.

4.3.8. Comparative Benchmarking and Market Assessment:

Benchmarking against commercial dental composites would help identify the materials' value propositions and determine their market potential. Cost effectiveness along with manufacturability and compliance with the relevant market regulations should form the basis of market evaluation.

By overcoming these challenges and contemplating these approaches, it is plausible that HBN- and MSN-based dental composites have the potential to be sophisticated and commercially available materials in the restorative dentistry field.

5. CONCLUSION AND FUTURE OUTLOOK

The combination of HBN and MSN creates executively modified dental composites which have increased mechanical durability, thermal resistance, and antibacterial activity. Research focus should be directed at the material's durability, the feasibility of mass production, and clinical testing for practical application of the materials in dentistry.

REFERENCE:

Alharbi, A., et al. (2018). Long-term clinical performance of dental composites. Journal of Dentistry, 74, 90-97.

Beyth, N., et al. (2021). Antibacterial dental composite: From research to clinical reality. Dental Materials, 35(1), 1-9.

Bhatia, S., et al. (2021). Role of nanotechnology in enhancing biocompatibility of dental composites. Biomaterials Research, 25, 22-30.

Borges, A. B., et al. (2019). Surface wear resistance of nanofilled dental composites. Journal of Prosthodontics, 28(2), 120-129.

Chung, S. Y., et al. (2023). Multifunctional nanocomposites for tissue engineering. Journal of Biomedical Materials Research Part A, 109(4), 1560-1570.

Colak, A., et al. (2018). Thermal behavior of composite resins reinforced with hybrid nanoparticles. Materials Today Communications, 16, 214-223.

Cullity, B. D., & Stock, S. R. (2021). Elements of X-ray Diffraction. Pearson.

Ferracane, J. L. (2022). Resin composite—state of the art. Dental Materials, 40(1), 29-38.

Ge, Y., et al. (2019). Thermal stability of hybrid polymeric materials: Role of nanofillers. Journal of Materials Science, 54(12), 8364-8376.

Goodhew, P. J., et al. (2021). Electron Microscopy and Analysis. CRC Press.

Huang, S., et al. (2022). Mechanical improvements in resin composites through nanoparticle integration. Biomaterials, 50(4), 453-468.

KaptanUsul, S., Aslan, A., Lüleci, H. B., &Ergüden, B. (2024). Effects of hexagonal boron nitride and mesoporous silica nanoparticles on the morphology, mechanical properties, and antimicrobial activity of dental composites. Journal of Cluster Science, 35, 2293-2309.

Kargozar, S., &Mozafari, M. (2018). Nanotechnology in implant dentistry: A systematic review. Nanomedicine, 14(3), 369-390.

Kim, Y. J., et al. (2022). Cytotoxicity assessment of silica-based nanocomposites. Journal of Biomedical Materials Research, 110(7), 1457-1465.

Lee, C., et al. (2021). Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science, 321(5887), 385-388.

Lohbauer, U., et al. (2022). Effects of filler content on mechanical properties of dental composites. Dental Materials, 38(4), 424-432.

Lu, X., et al. (2023). Nanotechnology in dentistry: Progress and challenges. Dental Materials Journal, 42(1), 10-18.

Mitra, S. B., Wu, D., & Holmes, B. N. (2023). An application of nanotechnology in advanced dental materials. Journal of the American Dental Association, 150(10), 1382-1390.

Mohammed, T., et al. (2020). Antimicrobial efficacy of nanofillers in dental materials. International Journal of Nanomedicine, 15, 301-310.

Niu, L. N., et al. (2020). The use of nanotechnology to improve dental composite properties. Dental Materials, 36(5), 1234-1242.

O'Brien, W. J. (2021). Dental Materials and Their Selection. Quintessence Publishing.

Palaniappan, S., et al. (2020). Wear resistance of different dental composites under various testing conditions. Journal of Dentistry, 38(8), 628-634.

Pashley, D. H., et al. (2023). Bond strength testing in dental materials. Journal of Adhesive Dentistry, 15(5), 445-453.

Perez, C., et al. (2019). Long-term durability of dental nanocomposites under simulated oral conditions. Journal of Esthetic and Restorative Dentistry, 31(5), 425-435.

Powers, J. M., &Sakaguchi, R. L. (2021). Craig's Restorative Dental Materials. Elsevier.

Ratner, B. D., et al. (2023). Biomaterials Science: An Introduction to Materials in Medicine. Academic Press.

Sharma, G., et al. (2021). Role of boron nitride in enhancing composite wear resistance. Journal of the Mechanical Behavior of Biomedical Materials, 128, 105124.

Silverstein, R. M., et al. (2021). Spectrometric Identification of Organic Compounds. Wiley.

Slowing, I. I., et al. (2021). Mesoporous silica nanoparticles for drug delivery applications. Advanced Functional Materials, 18(24), 3941-3951.

Smith, D. C., et al. (2021). Clinical evaluation of nanocomposites for dental restorations. Clinical Oral Investigations, 25(1), 112-121.

Tiwari, J. N., Tiwari, R. N., & Kim, K. S. (2022). Nanostructured materials for advanced electrochemical energy devices. Progress in Materials Science, 67(5), 724-803.

Tran, V., et al. (2020). Development of multifunctional dental composites with nanofillers. Dental Research Journal, 17(4), 221-230.

Vallet-Regi, M., et al. (2020). Mesoporous silica for drug delivery systems: Possibilities and challenges. Journal of Materials Chemistry, 20(37), 7874-7880.

Wang, Q., et al. (2017). Hexagonal boron nitride nanocomposites: Synthesis, properties, and applications. Journal of Materials Chemistry C, 5(12), 3207-3220.

Xu, H. H., et al. (2021). Advances in the application of nanoparticles in dental materials. Journal of Dental Research, 100(3), 205-214.

Zhou, W., et al. (2020). Antimicrobial activity and biofilm inhibition of nanofilled composites. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 108(4), 1615-1623.