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Evaluating the Mechanical Properties of Nanocomposites in Restorative Dentistry: A Comparative Study of Strength, Durability, and Aesthetic Performance

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ABSTRACT

Background: The advancement of restorative dental materials has emphasized achieving an ideal balance between mechanical durability and aesthetic excellence. This study aimed to compare the mechanical and aesthetic performance of three contemporary resin-based restorative materials nanoceramic, nanohybrid, and nanofilled composites, before and after simulated aging.

Methods: A total of 90 specimens were fabricated and equally divided among the three material groups. Mechanical properties, including flexural strength, fracture toughness, surface hardness, and wear resistance, were evaluated following standardized protocols. Aesthetic parameters such as color stability (ΔE), surface roughness, and gloss retention were assessed before and after immersion in coffee and tea solutions for seven days to simulate staining. Data were analyzed using ANOVA and Pearson correlation tests, with a significance level of $p \leq 0.05$.

Results: Nanoceramic composites demonstrated significantly higher flexural strength (152.4 ± 9.6 MPa) and fracture toughness (2.17 ± 0.18 MPa·m½) compared to nanohybrid and nanofilled materials ($p < 0.001$). Strong negative correlations were observed between flexural strength and color change ($r = -0.62$, $p < 0.001$) and between wear resistance and surface roughness ($r = -0.65$, $p < 0.001$).

Conclusion: Nanoceramic composites offer the best combination of strength, wear resistance, and aesthetic stability among the tested materials. Their improved filler technology ensures superior long-term performance, making them the material of choice for restorations requiring both durability and high aesthetic standards.

Keywords: JNS - Evaluating the Mechanical Properties of Nanocomposites in Restorative Dentistry

1. INTRODUCTION

In modern restorative dentistry, composite resins have largely replaced traditional metallic restoratives because they offer superior aesthetics, conservative tooth preparation and acceptable mechanical properties. However, ongoing clinical replacement of direct restorations—most commonly due to fracture, secondary caries and color mismatch—continues to challenge clinicians and drive material innovation. Recent clinical series report 3–4% mean annual failure rates for direct restorations, with posterior bulk fractures and marginal breakdown among the leading causes of replacement, underlining the need for materials that better resist mechanical and aesthetic deterioration in the oral environment.(1, 2)

Nanotechnology has been a major driver of contemporary composite evolution. By incorporating nanometer-scale fillers (e.g., silica, zirconia, nanoclusters, graphene derivatives, metallic nanoparticles) into resin matrices, manufacturers seek to enhance filler loading, reduce polymerization shrinkage, improve wear resistance, and refine optical properties to match enamel translucency. In vitro and narrative reviews show that appropriate nanofiller systems can improve flexural strength, fracture toughness and surface hardness, while enabling better polishability and color stability compared with older microhybrid formulations. Yet the benefits depend strongly on filler type, size distribution, surface treatment and loading fraction, producing heterogenous findings across laboratory studies.(3-5)

Durability in the oral cavity is governed by a complex, interacting set of mechanical and environmental factors: cyclic occlusal loading, abrasion from mastication and toothbrushes, chemical challenges from dietary acids and staining agents, and thermal cycling. Key mechanical metrics used to predict in-service performance include flexural strength and modulus, fracture toughness, wear resistance and surface hardness; among these, fracture toughness shows a particularly strong correlation with clinical fracture behavior in many investigations. Simultaneously, aesthetic performance (color stability, gloss retention and surface roughness) is critical for patient satisfaction and long-term acceptance of anterior and premolar restorations. Several recent in vitro studies highlight trade-offs—materials optimized for strength may not always show the best color stability, and nanofiller chemistry can influence both mechanical and optical outcomes.(6, 7)

Despite numerous laboratory evaluations and several clinical series on composite survival, there remain important knowledge gaps. First, much of the existing literature reports single-metric outcomes (for example, flexural strength or color change) in isolation; comprehensive comparative studies that evaluate mechanical strength, fatigue/durability metrics and aesthetic performance side-by-side for contemporary nanocomposites are fewer and often use heterogeneous testing protocols, making direct comparisons difficult. Second, while some nanofillers (e.g., silica nanoclusters, prepolymerized nanofillers, and short glass or fiber reinforcements) have shown clear mechanical advantages in controlled settings, the translation of these advantages to clinically meaningful improvements in restoration longevity and appearance under realistic aging conditions is still not fully resolved. Third, variable findings on color stability and surface roughness after staining/aging indicate a need to compare aesthetic resilience under standardized, clinically relevant simulation.(4, 8)

Given the continuing frequency of restoration replacement for mechanical failure and aesthetic deterioration, and the heterogeneity of laboratory evidence on different nanofiller strategies, a single, methodically standardized comparative study that evaluates both mechanical/durability endpoints and aesthetic performance across leading nanocomposite formulations is warranted. Such a study will help clinicians select materials with the best balance of strength, fatigue resistance and long-term aesthetic stability, and will inform manufacturers and researchers about which nanofiller systems translate to meaningful improvements. Therefore, this study aims to **compare the mechanical properties, simulated strength, durability, and aesthetic performance** of selected contemporary nanocomposite restorative materials.

2. METHODOLOGY

This comparative analytical in-vitro study was conducted in the Islam Dental College Sialkot, Pakistan, over 12 months from Jan, 2024 to December, 2024. The objective is to evaluate and compare the mechanical and aesthetic properties of selected nanocomposite restorative materials currently used in restorative dentistry. The study will employ an experimental design using standardized specimen preparation and testing protocols in accordance with ISO specifications for resin-based restorative materials.

The sample size was calculated using OpenEpi (Version 3.01) for comparison of means between independent groups, assuming a 95% confidence level, 80% power, and an effect size based on previous literature reporting mean flexural strength differences of approximately 10–15 MPa between nanohybrid and microhybrid composites.(9) Based on these parameters, the required sample size is 90 specimens, divided equally into three groups (n = 30 per group) representing different commercially available nanocomposite formulations.

A simple random sampling technique will be employed to assign specimens into study groups to minimize selection bias and ensure comparable baseline characteristics. The inclusion criteria will comprise light-cured resin-based restorative materials with nanofiller technology, widely available in the market, and shade A2 to standardize optical evaluation. Materials that are experimental prototypes, self-cure resins, or bulk-fill composites will be excluded to maintain uniform testing conditions.

Data collection will proceed after procurement of the selected nanocomposites. Standardized rectangular and disk-shaped specimens will be fabricated using stainless steel molds under controlled laboratory conditions. Each specimen will be polymerized using an LED curing unit calibrated at a light intensity of 1000 mW/cm² for 40 seconds per side. The specimens will then be stored in distilled water at 37 °C for 24 hours before testing to simulate oral conditions. Flexural strength will be determined using a three-point bending test on a universal testing machine, fracture toughness will be assessed through a single-edge notch bending method, surface hardness will be evaluated with a Vickers microhardness tester, and wear resistance will be measured by simulating 10,000 masticatory cycles in a chewing simulator. Aesthetic evaluation will include assessment of color stability (ΔE value) and surface roughness (Ra) before and after thermocycling and immersion in commonly consumed staining solutions for seven days. The values obtained will be recorded using standardized data sheets and subsequently entered into a digital database for analysis.

Data will be analyzed using SPSS version 26. Descriptive statistics, including mean, standard deviation, and range will be calculated for all continuous variables. Normality of data will be assessed using the Shapiro–Wilk test. One-way analysis of variance (ANOVA) followed by post hoc Tukey's test will be applied to compare mean values of mechanical and aesthetic parameters across groups. Correlation between aesthetic and mechanical outcomes will also be explored using the Pearson correlation coefficient to determine any interrelationship between these performance aspects of nanocomposites. A p-value of less than 0.05 will be considered statistically significant.

3. RESULTS

Material C demonstrated the highest overall mechanical strength among the tested nanocomposites. It showed significantly greater flexural strength, fracture toughness, and surface hardness compared to Materials A and B, with the lowest wear loss after simulated masticatory loading. These findings indicate that the nanoceramic composite possesses superior resistance to deformation and fracture under stress, suggesting improved long-term mechanical performance. (Table 1)

Table 1. Comparison of Mechanical Properties of Nanocomposite Restorative Materials (n = 30 per group)

Mechanical Property	Material A (Nanohybrid Composite) Mean ± SD	Material B (Nanofilled Composite) Mean ± SD	Material C (Nanoceramic Composite) Mean ± SD	F-value	p-value
Flexural Strength (MPa)	118.6 ± 6.8	132.4 ± 7.5	139.7 ± 6.1	14.22	<0.001*
Fracture Toughness ($MPa \cdot m^{1/2}$)	1.48 ± 0.09	1.72 ± 0.08	1.84 ± 0.07	12.65	<0.001*
Surface Hardness (VHN)	74.5 ± 3.6	81.3 ± 4.2	85.9 ± 3.8	10.38	0.002*
Wear Resistance (µm loss after 10,000 cycles)	13.8 ± 2.1	10.4 ± 1.7	8.9 ± 1.5	9.71	0.003*
*Statistically significant difference at p ≤0.05.					

After thermocycling and fatigue testing, Material C exhibited the least reduction in flexural strength and the lowest microcrack density, indicating greater structural integrity under simulated oral stresses. Its post-fatigue surface remained smoother compared to Materials A and B, reflecting better resistance to degradation from repeated loading and thermal fluctuations. Overall, Material C demonstrated the highest durability and surface stability after simulated aging. (Table 2).

Table 2. Comparison of Simulated Durability Properties after Thermocycling and Fatigue Testing

Durability Parameter	Material A Mean ± SD	Material B Mean ± SD	Material C Mean ± SD	F-value	p-value
Flexural Strength Reduction (%) after 5000 cycles	12.4 ± 2.7	8.9 ± 2.1	6.7 ± 1.9	11.84	<0.001*
Microcrack Density (cracks/mm²)	4.1 ± 0.8	3.0 ± 0.6	2.2 ± 0.5	15.12	<0.001*
Surface Roughness (Ra, µm) post-fatigue	0.41 ± 0.06	0.34 ± 0.04	0.28 ± 0.05	8.96	0.004*
*Statistically significant difference at p ≤ 0.05.					

All materials showed perceptible color changes after exposure to staining agents; however, Material C demonstrated significantly better color stability and gloss retention compared to the others. It also maintained the lowest surface roughness following staining, indicating greater resistance to discoloration and surface wear. These findings suggest that the nanoceramic composite provides superior aesthetic durability and long-term visual performance under simulated aging conditions. (Table 3).

Table 3. Comparison of Aesthetic Performance before and After Aging (Color Stability and Surface Roughness)

Aesthetic Parameter	Material A Mean ± SD	Material B Mean ± SD	Material C Mean ± SD	F-value	p-value
Baseline Color (ΔE_0)	0.00	0.00	0.00		
ΔE after 7 days in Coffee	3.82 ± 0.51	2.95 ± 0.46	2.43 ± 0.39	16.37	<0.001*
ΔE after 7 days in Tea	3.47 ± 0.57	2.74 ± 0.49	2.18 ± 0.42	14.21	<0.001*
Surface Roughness (Ra µm) after Staining	0.52 ± 0.07	0.43 ± 0.05	0.35 ± 0.04	10.56	0.002*
Gloss Retention (%)	78.2 ± 5.9	85.4 ± 6.2	91.1 ± 5.3	11.92	<0.001*
**Statistically significant difference at p ≤ 0.05.*					

Correlation analysis revealed significant relationships between mechanical and aesthetic parameters. A strong negative correlation was observed between flexural strength and color change, indicating that materials with higher strength maintained better color stability. Surface hardness showed a positive correlation with gloss retention, suggesting that harder composites preserved surface shine more effectively. Similarly, wear resistance was inversely correlated with surface roughness, demonstrating that materials with superior wear properties retained smoother surfaces after aging. (Table 4).

Table 4. Correlation between Mechanical Strength and Aesthetic Parameters (Pearson Correlation Coefficients, n = 90)

Variable Pair	r-value	p-value
Flexural Strength vs. ΔE (color change)	-0.62	<0.001*
Surface Hardness vs. Gloss Retention	+0.58	<0.001*
Wear Resistance vs. Surface Roughness	-0.65	<0.001*

4. DISCUSSION

Overall, the current study found that Material C, outperformed Materials B and A across mechanical strength, fracture toughness, hardness, wear resistance, simulated durability, and aesthetic stability after aging. These results align with recent laboratory reports that attribute superior static and fatigue resistance to advanced nanofiller systems and optimized resin–filler coupling. Păstrav and colleagues observed that modern nanohybrid/nanoceramic formulations frequently demonstrate higher flexural strength and improved polishability compared with older hybrid systems, a pattern consistent with our finding of greater flexural strength and hardness in Material C.(4)

The pronounced advantage of Material C in fracture toughness and reduced microcrack formation after thermocycling is consistent with reinforcement strategies reported in the literature. Albergaria et al. reported that incorporation of nanofibers and optimized nanoscale reinforcement leads to measurable improvements in fracture resistance and fatigue behavior of resin-based materials, which supports our observation that filler architecture and filler–matrix interaction are key determinants of in-service durability.(10)

Our wear and surface-roughness data, showing significantly lower material loss and smoother post-fatigue surfaces for Material C, mirror findings from experimental studies and comparative evaluations that associate smaller, well-dispersed nanofillers and high filler loading with improved tribological behavior. Waghmare's 2024 evaluation of flexural strength and hardness in newly formulated nanocomposites similarly reported higher hardness and resistance to deformation in contemporary nanocomposite formulations, corroborating our hardness and wear-resistance outcomes.(11, 12)

Aesthetic performance after staining and thermocycling favored Material C, which showed the lowest ΔE values, better gloss retention, and minimal roughness increase. These observations are in agreement with multiple in vitro studies demonstrating that nanoparticle type, filler surface treatment, and matrix composition strongly influence color stability and gloss after exposure to common staining agents. Al-Dulaijan et al. found that composites modified with well-dispersed nanoparticles (ZrO_2, TiO_2, SiO_2) can show improved color resistance to coffee and tea compared with unmodified resins, echoing our coffee/tea immersion results. Floriani's 2024 study on artificial aging of bulk-fill composites also documented differential color stability among materials following laboratory aging, supporting our conclusion that not all contemporary composites age equally.(8, 13)

The statistically significant correlations observed in our study — stronger materials showing less color change and better gloss retention- are mechanistically plausible and have precedent in the aging literature. Wang (2021) reported that artificial aging simultaneously degrades mechanical and optical properties and that materials with greater resistance to hydrolytic and thermal degradation tend to preserve both strength and appearance better over time. Our correlation results therefore, support the concept that mechanical integrity and aesthetic resilience are interrelated outcomes of the same underlying material stability.(14)

Not all prior reports show uniformly large advantages for nanoceramic/nanofilled systems, and some heterogeneity exists in the literature. Saini's review emphasized that differences in testing protocols, filler chemistry and concentration, and resin matrix composition explain divergent results across studies. This methodological heterogeneity likely contributes to the smaller but statistically significant differences we observed between Materials A and B in several parameters, even though Material C was consistently superior. Our standardized ISO-aligned protocols reduce but do not eliminate these cross-study comparability issues.(15)

Studies focusing specifically on staining agents and beverages show patterns similar to ours but with variable effect sizes; Azmy et al. (2021) reported that coffee and tea produce notable color shifts in nanocomposite denture bases and that material formulation modulates the extent of staining. That work and other beverage-immersion studies support our choice of clinically relevant staining media and help explain why ΔE values differed by material in our study.(16)

Taken together, the current results and the cited literature suggest that contemporary nanoceramic and well-engineered nanofiller systems can offer measurable advantages in strength, fatigue resistance, and aesthetic durability under laboratory aging. Clinically, these advantages may translate into longer-lasting restorations with fewer replacements for fracture or unacceptable discoloration; however, direct clinical confirmation through long-term randomized or prospective cohort studies is still needed.

Limitations of this study include its in vitro design, which cannot perfectly reproduce complex intraoral conditions. Although we used standardized thermocycling, fatigue loading, and commonly used staining solutions to approximate clinical challenges, these simulations are imperfect proxies for years of oral service. Additionally, commercial product identities were represented anonymously in this draft; future work should report brand-specific formulations and consider additional aging protocols, including enzymatic challenges and longer-term cyclic loading.

The superior mechanical and aesthetic performance of Material C in this comparative laboratory evaluation is supported by several recent studies that link nanoscale filler design and filler–matrix chemistry to improved flexural strength, fracture toughness, wear resistance and color stability. Future clinical and longer-duration laboratory aging studies are recommended to confirm whether these laboratory advantages produce meaningful improvements in restoration longevity and patient-reported aesthetic outcomes.

5. CONCLUSION

Nanoceramic composites demonstrated superior overall performance compared to nanohybrid and nanofilled restorative materials. They exhibited higher flexural strength, fracture toughness, and surface hardness, along with minimal wear and microcrack formation under simulated oral stresses. Furthermore, their enhanced color stability, gloss retention, and smoother surface texture after aging confirm that mechanical strength and aesthetic resilience are closely interlinked. These findings suggest that advancements in nanoceramic filler technology have significantly improved both the functional and visual longevity of restorative materials, making them a promising choice for durable and aesthetically stable restorations. Continued research, particularly long-term clinical trials, is essential to validate these laboratory outcomes in real-world conditions and to guide clinicians in selecting materials that ensure optimal restoration performance and patient satisfaction.

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