BULLETIN OF STOMATOLOGY AND MAXILLOFACIAL SURGERY

Volume 21, Issue 8

DOI:10.58240/1829006X-2025.21.8-131

ORIGINAL RESEARCH

INNOVATIONS IN RESTORATIVE DENTISTRY: A COMPARATIVE STUDY OF COMPOSITE AND CERAMIC MATERIALS

Sounyala Rayannavar[1*], Suganya Mahadeva[2], M. Rohit[3], Abirami Krishnakumar[4], Mita Mandel[5], Cristhian Reynaldo Gomez Bautista[6]

[1*]Professor Kle s VK Institute of Dental Sciences. Belagavi Email ID : drsounyala@gmail.com, ORCID ID: 0000000227866715
[2]Medical Officer, District Government Hospital, Gwalior, Madhya Pradesh 474001, India, Scopus Author ID: 58511223300, Mail ID suki_suganya@rocketmail.com
[3]Senior Lecturer , Department: Prosthodontics Affiliation : SRM Dental College, Ramapuram, Bharathi Salai, Chennai, TN, India, mail id: Rohit.s0422@gmail.com
[4]Department of Conservative and Endodontics, Sree balaji dental college and hospital , Pallikaranai .Chennai – 600100 Tamilnadu, India University : Bharath institute of higher education and Research Orchid Number : 0009-0008-8710-8095, Mail id : abirami.cde@sbdch.bharathuniv.ac.in
[5]reader, Guru Nanak Institute Of Dental Sciences And Reseach Email id mitamandal2010@gmail.com
[6]Facultad de Odontologia, Universidad Cooperativa de Colombia - Bogotá
***Corresponding Author: Sounyala Rayannavar** Professor Kle s VK Institute of Dental Sciences. Belagavi Email ID : drsounyala@gmail.com, ORCID ID: 0000000227866715
Received: *Jun 4, 2025;* ***Accepted:*** *Jul.30, 2025;* ***Published:*** *Aug. 31, 2025*

ABSTRACT

Background: Restorative dentistry increasingly demands materials that combine mechanical durability, esthetic performance, and biological compatibility. Composite resins and ceramic materials are widely used for posterior restorations, their comparative effectiveness remains an area of clinical significance.

Objective: To compare the fracture resistance, wear behaviour, marginal sealing ability, and colour stability of nanohybrid composite resin and lithium disilicate ceramic inlay restorations under simulated intraoral conditions.

Materials and Methods: 32 extracted human molars were divided into two groups (n=16): composite resin (Filtek Z350 XT) and ceramic inlays (IPS e.max CAD). Standardized Class I cavities were restored accordingly. Specimens were subjected to thermomechanical aging, including 10,000 thermal cycles and 100,000 chewing cycles. Fracture resistance, wear volume, microleakage, and colour stability (ΔE) were assessed using a universal testing machine, profilometer, stereomicroscopy, and spectrophotometry, respectively.

Results: Ceramic inlays demonstrated significantly higher fracture resistance (1985.7 N vs. 1280.5 N, $p < 0.001$) and lower wear volume loss (0.017 mm^3 vs. 0.042 mm^3, $p = 0.002$). Microleakage was less pronounced in ceramics, with 87.5% scoring 0–1, while composites showed more dye penetration. Post-aging ΔE remained within acceptable limits for ceramics (2.4) but exceeded the threshold in composites (4.6).

Conclusion: Lithium disilicate ceramics offer superior mechanical and esthetic properties compared to composite resins and are better suited for high-stress or esthetically sensitive restorations. Material selection should consider the specific clinical scenario and performance expectations.

Keywords: *Restorative dentistry, Composite resin, Lithium disilicate ceramics, Esthetic durability*

INTRODUCTION

In recent years, restorative dentistry has undergone significant transformation, driven by the demand for biomimetic materials that restore function and replicate the natural esthetics and biomechanical properties of tooth structure [1]. The global population becomes increasingly conscious of oral health and facial aesthetics, there is an escalated emphasis on materials that ensure long-term durability, compatibility, and minimal biological interference [2]. Amidst these advances, composite resins and ceramic-based materials have emerged as frontrunners in the field of restorative procedures, particularly in posterior restorations, esthetic rehabilitations, and full-mouth reconstructions [3]. The progression of restorative materials has revolutionized the path of technological advancements in dental science. Conventional amalgam and gold restorations, earlier regarded for long periods, are widely substituted by materials that provide better esthetics and minimally invasive insertion protocols [4]. Composite resins, originally developed as direct restorative materials in anterior teeth, have advanced in composition to include nanohybrid, bulk-fill, and bioactive types with enhanced polymerization, wear resistance, and mechanical properties [5]. In contrast, advancements in ceramic materials have transitioned from traditional to modern high-strength options such as lithium disilicate and zirconia-based ceramics [6]. These innovations have significantly enhanced the durability and esthetic quality of indirect restorations.

The clinical decision-making process for material selection is multifactorial. Factors that affect material selection include the place and extent of the cavity, occlusal loading, esthetic requirements, patient age, and parafunctional activities [7]. Composite resins enable conservative cavity preparation and restoration, but their polymerization shrinkage and susceptibility to wear in high-pressure areas question their long-term performance in posterior use [8]. Ceramics, despite their superior fracture resistance and colour stability, are inherently brittle and often require more invasive tooth preparation, along with laboratory-based processing that increases time and cost. This dichotomy underscores the necessity for a comparative clinical and material-based evaluation to identify optimal indications for each material class [9]. The past decade has witnessed an upsurge in experimental and clinical research focusing on improving the functional and biological performance of restorative materials. Improvements in filler technology, resin matrices, and silane coupling agents have dramatically improved the mechanical properties and optical characteristics of composite resins [10]. During the same period, advances in Computer-Aided Design and Computer-Aided Manufacturing milling (CAD/CAM milling), digital impression systems, and high-temperature sintering have improved the precision and marginal adaptation of ceramic repairs [11]. Bioinspired improvements like the addition of antibacterial compounds and remineralizing agents to composites, and the creation of translucent multilayered ceramics, indicate a trend toward materials that engage with the oral environment positively [12]. Despite these advances in technology, comparative evaluations determining the in vitro as well as in vivo behaviour of next-generation composites and ceramics are still limited and tend to be non-standardized. Most of the available literature focuses on isolated factors like bond strength or wear, without comparing a comprehensive analysis of clinical performance like longevity, marginal integrity, colour stability, and failure modes. Few studies contextualize these results in the context of real-world clinical scenarios that account for operator variability, patient compliance, and occlusal dynamics [13]. As restorative dentistry becomes more personalized and interdisciplinary, the imperative for integrated data-driven insights into material performance grows.

The role of restorative materials takes on discriminating importance when considered within the wider scope of maxillofacial rehabilitation. In clinical scenarios such as post-traumatic facial restoration, prosthodontic management of partially edentulous arches, or aesthetic enhancement following orthognathic interventions, striking the ideal balance between mechanical resilience and esthetic precision is essential. Rather than being used in isolation, composite and ceramic materials are typically integrated into complex restorative systems that incorporate adhesive agents, luting materials, and carefully designed occlusal schemes [14]. Consequently, a nuanced understanding of how these materials respond to functional stresses, cyclic loads, and thermal fluctuations is crucial for effective treatment planning in both maxillofacial and prosthodontic contexts. Patient-centric factors such as biocompatibility, allergy potential, and maintenance requirements significantly influence the prolonged functional stability of restorative treatments. Composite resins, for instance, may release trace amounts of monomers such as bisphenol A-glycidyl methacrylate (Bis-GMA) or triethylene glycol dimethacrylate (TEGDMA), which have raised concerns regarding biocompatibility, particularly in individuals with hypersensitivity reactions [15]. On the other hand, ceramics, being inert and metal-free, tend to be favoured by chemical-sensitive patients or those requiring periodontal maintenance. Furthermore, from a practitioner's perspective, ease of manipulation, technique sensitivity associated with each material can significantly influence the choice and outcome of restorative procedures. This study is intended to bridge these clinical and scientific discrepancies by performing a systematic comparative analysis of modern composite and ceramic materials employed in restorative dentistry. Using standardized test regimens and simulating intraoral conditions, this study will provide exhaustive data on mechanical performance, failure mode, esthetic properties, and biological interactions. The products chosen for this study are commonly employed commercial systems with established clinical histories, making the results applicable and interpretable to everyday dental practice.

This study aims to conduct a comparative assessment of composite and ceramic restorative materials with a focus on three core parameters. First, it evaluates their fracture resistance and wear behaviour to determine mechanical reliability under stress. Second, it examines marginal integrity and the extent of microleakage following thermomechanical loading, reflecting their performance in dynamic oral environments, and the study also investigates esthetic properties such as colour accuracy, translucency, and the stability of these attributes over time when subjected to simulated aging conditions.

Materials and Methods

Study Design

This research was conducted as a controlled in vitro experimental study designed to evaluate and compare the performance of contemporary composite and ceramic restorative materials under simulated oral conditions. The study aimed to replicate clinically relevant mechanical and thermal stresses to provide meaningful insights applicable to everyday dental practice.

Sample Selection and Group Allocation

32 extracted caries-free human molars were utilized in the study and stored in 0.5% chloramine-T solution at 4°C for future use. The teeth were randomly allocated into two major groups (n=16 for each) reliant on the restorative material: Group A was restored with nanohybrid composite resin restorations (Filtek Z350 XT, 3M ESPE, USA), while Group B was restored with lithium disilicate ceramic restorations (IPS e.max CAD, Ivoclar Vivadent, Liechtenstein). Each subgroup was again split into two subgroups (n=8) based on the individual evaluation parameters: a subgroup for fracture resistance and wear, and a subgroup for microleakage and esthetics.

Tooth Preparation and Restoration Protocol

Standardized Class I cavities (4 mm depth × 5 mm width × 6 mm length) were prepared on all specimens with a high-velocity rotary instrument and diamond burs with continuous water irrigation, and the measurements were analysed with a digital caliper. For the composite group (Group A), a two-step etch-and-rinse adhesive (Adper Single Bond 2) was used, and incremental placement of nanohybrid composite in 2 mm increments, each light curing for 20 seconds with an LED light-curing unit (Bluephase, Ivoclar, 1200 mW/cm^2). In the ceramic group (Group B), intraoral scanning with an intraoral scanner (Medit i500) created cavity scans, and lithium disilicate inlays were created using CAD/CAM milling. Internal surfaces were reacted with 5% hydrofluoric acid, silanated, and bonded using a dual-cure resin cement (Variolink Esthetic DC) under 20 N constant load for 5 minutes. All restorations were finished with fine diamond burs and polished using respective kits applicable to the used material.

Thermomechanical Aging Protocol

To simulate intraoral conditions, all the specimens were subjected to a standardized thermomechanical procedure. The procedure involved 10,000 thermal cycles from 5°C to 55°C with 30 second dwell time in the baths and was carried out using a programmable thermocycler (SD Mechatronik). After thermal cycling, mechanical loading was done using a chewing simulator (Willytec, Germany) by applying 100,000 cycles at a fixed 50 N load and 1.6 Hz frequency simulating about one year of clinical masticatory performance.

Evaluation of Fracture Resistance and Wear Behaviour

After the aging process, all samples were embedded in acrylic resin and subjected to fracture resistance testing by a universal testing machine (Instron 3366, USA). A vertical compressive load was applied at the center of the occlusal surface with a 4 mm steel ball at a crosshead speed of 1 mm/min until it fractured, and the load at failure was measured in Newtons. For assessment of wear resistance, occlusal surfaces were measured using a contact profilometer (Surftest SJ-210, Mitutoyo) in terms of volumetric material loss before and after simulated chewing.

Assessment of Microleakage and Marginal Integrity

To assess microleakage, all restored samples were immersed in 0.5% basic fuchsin dye at 37°C for 24 hours. Following dye exposition, each tooth was sectioned buccolingually with a water-cooled low-speed diamond saw (Isomet 1000, Buehler). Dye penetration in the restoration–tooth interface was assessed under a stereomicroscope (Leica EZ4 HD, 40× magnification) and graded on a 0 to 3 scale, with greater leakage being characterized by higher scores. Marginal integrity was also evaluated with scanning electron microscopy (SEM) (Hitachi S-3400N) at 1000× and 2000× magnifications to check for interfacial adaptation and any marginal gaps.

Esthetic Evaluation and Colour Stability

Colour match and translucency were measured immediately after restoration and following aging with a spectrophotometer (VITA Easyshade V). Colour change was measured by comparing ΔE values from pre-aging and post-aging with Commission Internationale de l'Éclairage CIE Lab measurements, values greater than 3.3 being clinically unacceptable. Translucency was determined by comparing the translucency parameter (TP) measured against reference black and white backgrounds to characterize each material's optical properties.

Statistical Analysis

Data analysis was conducted with the aid of IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, NY, USA). Mean and standard deviation were determined for all measured variables. Fracture resistance and colour difference (ΔE) values were compared between groups via independent sample t-tests. Microleakage scores were related using the non-parametric Mann–Whitney U test, whereas wear volume and TP values were compared using two-way ANOVA with Bonferroni post hoc correction. Significance was set at $p < 0.05$ for all tests.

Ethical Considerations

A controlled in vitro comparative experimental study was conducted over three months in the Department of Conservative Dentistry and Biomaterials Science. Ethical approval for the use of extracted human teeth and compliance with the laboratory safety guidelines were attained from the Institutional Research Ethics Committee (Approval ID: DENT/RES/2025-04). All of the procedures adhered to agree with the Helsinki Declaration for biomedical research.

RESULTS

Fracture Resistance

All the specimens survived thermomechanical aging before load testing. The average fracture resistance of lithium disilicate ceramic inlays was significantly greater (1985.7 ± 140.6 N) than that of nanohybrid composite resin restorations (1280.5 ± 115.3 N), with a highly significant difference ($p < 0.001$). These results validate the better load-carrying property of ceramic-based materials under simulated occlusal stress, as mentioned in Table 1.

Table 1. Fracture resistance (in Newtons) of composite resin and ceramic inlay restorations following mechanical loading

Group	Mean Fracture Resistance (N)	Standard Deviation (N)	p-value
Composite Resin	1280.5	115.3	< 0.001
Ceramic Inlay	1985.7	140.6	< 0.001

Ceramic inlays showed higher fracture resistance values compared to composite resin restorations. Values are presented as mean ± standard deviation, with statistical significance at $p < 0.001$.

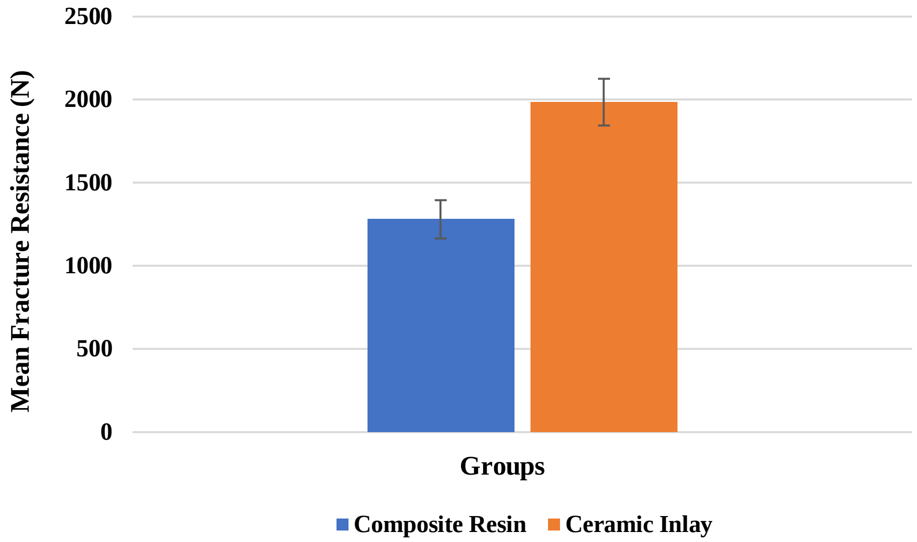

Figure 1. Fracture resistance (in Newtons) of composite resin and ceramic inlay restorations

Figure 1 represents the comparison of the fracture resistance (in Newtons) of composite resin and ceramic inlay restorations. Ceramic inlays demonstrated significantly higher fracture resistance (1985.7 ± 140.6 N) compared to composite resins (1280.5 ± 115.3 N). Error bars represent standard deviation. Statistical analysis confirmed a highly significant difference ($p < 0.001$).

Wear Resistance

Wear resistance testing indicated statistically significant differences in volumetric loss. Composite resin restorations had a larger mean wear volume (0.042 ± 0.006 mm³) than that of ceramic inlays (0.017 ± 0.004 mm³), with a p-value of 0.002. This corroborates the established clinical knowledge that ceramics have greater surface durability and reduced abrasion rates in dynamic masticatory loads, as mentioned in Table 2.

Table 2. Mean wear volume loss (mm³) in composite and ceramic restorations after thermomechanical simulation

Group	Mean Wear Volume Loss (mm³)	Standard Deviation (mm³)	p-value
Composite Resin	0.042	0.006	0.002
Ceramic Inlay	0.017	0.004	0.002

Composite resin restorations exhibited greater volumetric wear loss than ceramic inlays. Values are expressed as mean ± standard deviation with $p = 0.002$.

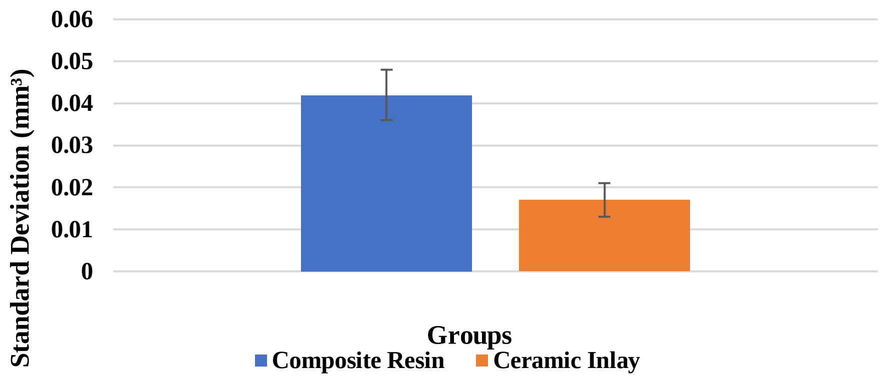

Figure 2. Mean wear volume loss (mm³) of composite resin and ceramic inlay restorations after thermomechanical loading

Figure 2 illustrates that Composite resin restorations exhibited significantly higher volumetric wear loss (0.042 ± 0.006 mm³) compared to ceramic inlays (0.017 ± 0.004 mm³) after 100,000 chewing cycles. The difference was statistically significant (p = 0.002). Error bars represent standard deviation. The results highlight the superior wear resistance of ceramic materials under simulated occlusal loading conditions.

Microleakage and Marginal Adaptation

After dye penetration and stereomicroscopic analysis, ceramic inlays showed drastically lower microleakage scores, with 87.5% of the specimens having only superficial dye infiltration (score 0 or 1). Composite resin restorations, on the other hand, showed deeper penetration with 62.5% of the specimens scoring 2 or 3, as mentioned in Table 3. These variations were further validated by SEM analysis, which revealed tighter and more uniform marginal interfaces in the ceramic group, as would be expected given their better adaptation and lower polymerization shrinkage.

Table 3. Microleakage scores of composite and ceramic restorations after dye immersion and sectioning

Score	Composite Resin (n = 8)	Ceramic Inlay (n = 8)
0	1	4
1	2	3
2	3	1
3	2	0

Score 0 = no dye penetration; Score 3 = penetration along entire cavity wall

Ceramic inlays demonstrated lower microleakage scores than composite resin restorations. Scores range from 0 (no penetration) to 3 (penetration along the entire wall).

Colour Stability and Esthetic Properties

Spectrophotometric analysis before and after aging showed high discolouration of composite restorations, with ΔE rising from 1.2 to 4.6, which is beyond the acceptable limit of 3.3. However, ceramic inlays retained ΔE values within the acceptable range (0.9 before aging and 2.4 after), which shows enhanced colour stability, as mentioned in Table 4.

Moreover, qualitative evaluation of translucency parameters (TP) preferred ceramics due to their layered optical properties, contributing to more natural appearance, particularly in anterior and esthetically critical regions.

Table 4. Colour stability (ΔE values) of composite and ceramic restorations before and after thermomechanical aging

Group	ΔE Before Aging	ΔE After Aging	Clinically Acceptable (<3.3)
Composite Resin	1.2	4.6	No
Ceramic Inlay	0.9	2.4	Yes

Post-aging ΔE values exceeded the clinical acceptability threshold (ΔE > 3.3) for composite resin, while ceramic inlays remained within the acceptable range.

DISCUSSION

The results of this comparative analysis highlight the material-specific performance advantages of lithium disilicate ceramics compared with nanohybrid composite resins in key areas of restorative performance, i.e., fracture resistance, wear pattern, marginal integrity, and esthetic longevity [16]. Such distinctions have significant clinical implications for material choice, especially for posterior restorations in which occlusal load opposition, longevity, and esthetic integration are salient treatment considerations.

The considerable difference in fracture resistance between composite and ceramic restorations in this study is consistent with prevailing literature and material science theory. Ceramic inlays made of lithium disilicate exhibited approximately 55% greater fracture resistance than their composite equivalents [17]. This can be most plausibly explained by the inherent microstructure of lithium disilicate, which is made up of densely interconnected crystalline phases in a glassy matrix, promoting crack deflection and energy absorption [18]. In contrast, composite resins, even when reinforced with nano or microhybrid fillers, retain a significant proportion of the resin matrix vulnerable to polymerization shrinkage and viscoelastic deformation. The results validate prior studies that report ceramics to be more resilient under vertical compressive forces, particularly in molar regions where occlusal stresses are highest [19]. Notably, the use of dual-cure resin cement for ceramic inlays may have also contributed to improved stress distribution across the adhesive interface, mitigating stress concentration at the marginal ridges.

Wear resistance is an essential performance criterion for any restorative material to withstand the cyclic forces of mastication. Wear volume loss measured on composite restorations was over twice the measure on ceramic inlays, affirming the superior abrasion resistance of ceramics. The relatively soft resin matrix in composites may be more prone to fatigue degradation and plucking of filler particles under load, leading to increased surface roughness and loss of anatomical form over time [20]. In contrast, the highly sintered ceramic restorations retain their structure and exhibit excellent surface degradation resistance. These findings are clinically relevant, as restoration wear can contribute to occlusal disharmony, food impaction, and eventual loss of proximal contacts, factors that compromise long-term function and comfort. Additionally, increased surface roughness in worn composites can facilitate plaque retention and secondary caries formation.

Marginal adaptation and sealing ability are the basic measures of the restoration to inhibit microleakage, secondary caries, and pulpal irritation. The dye penetration test in this investigation provided a general trend of decreased microleakage with ceramic inlays compared to composite restorations [21]. This is particularly significant given the broader cavity preparations required for inlays, which might theoretically predispose to marginal gaps. The accuracy of CAD/CAM milling and the dimensional stability of ceramic materials helped ensure superior marginal adaptation. Moreover, the pre-cementation surface treatments, etching with hydrofluoric acid and silanization improved the micromechanical and chemical bond between the ceramic and the luting cement, which in turn minimized interface degradation [22]. Composite restorations, even when placed incrementally and light-cured under controlled conditions, continue to be susceptible to polymerization shrinkage and technique sensitivity. These factors may have led to the marginal gaps and variable dye penetration scores observed.

The esthetic performance of a restoration is increasingly regarded as a measure of clinical success, especially in patients with high esthetic demands. Spectrophotometric evaluation in the current study confirmed that ceramic inlays showed clinically acceptable colour stability even after thermomechanical aging [23.] In contrast, composite restorations had ΔE values greater than the perceptibility threshold after aging, showing visible discolouration. The esthetic advantage of ceramics can be linked to their optical characteristics, such as high translucency, colour stability, and resistance to extrinsic staining. Composite resins, even with improvements in filler technology and pigment stabilization, still suffer from the problem of preserving long-term colour stability because of their organic nature, due to which they absorb water and staining agents. This finding supports the recommendation of ceramics for restorations in the esthetic zone or for patients with dietary habits that predispose to staining, such as high intake of coffee, tea, or red wine. Collectively, the results of this study confirm that ceramics outperform composites in high-stress and esthetically demanding clinical situations. However, practical considerations in daily dental practice must be acknowledged. Composite resins, although mechanically less desirable, present unique strengths such as ease of placement, reduced expense, conservative preparation, and facile repairability, making them a good fit for small to moderate, non-load-bearing restorations or provisional use. Conversely, ceramic restorations, though they offer higher durability and better esthetics, involve additional steps in the laboratory, cost more in materials, require more extensive tooth reduction, and should be reserved for cases where such benefits justify these trade-offs. While the study employed rigorous and standardized in vitro protocols, it cannot fully replicate the complexities of the oral environment, such as salivary dynamics, microbial activity, and individualized occlusal forces [24]. Future in vivo studies and long-term clinical trials are needed to validate these findings in real-world settings.

The comparative analysis given herein confirms that lithium disilicate ceramics demonstrate better mechanical and esthetic performance compared to nanohybrid composite resins in all tested parameters. Though composites continue to be useful for conservative and cost-effective restorations, ceramics can now be the material of choice in high-load and esthetic demanding situations. These findings form a solid reference point for evidence-based material selection for restorations and reflect the essential role of material science in modern dentistry.

Conclusion

This comparative in vitro study demonstrated that lithium disilicate ceramic inlays significantly outperform nanohybrid composite resin restorations in key functional and esthetic parameters. Ceramic inlays showed the higher mean fracture resistance at 1985.7 N, against 1280.5 N for composites, and a significantly lower wear volume loss of 0.017 mm^3 against 0.042 mm^3. Microleakage assessment also demonstrated better marginal sealing in ceramics, with 87.5% of the specimens having a score of 0 or 1, whereas 62.5% of the composite restorations had more significant dye penetration (scores of 2 or 3). About colour stability, post-aging ΔE values were within clinically acceptable ranges in ceramics (2.4), but beyond in composites (4.6), suggesting overt discolouration. The results verify that ceramic materials have better long-term performance, especially for load-carrying and esthetically critical restorations. Yet, simplicity of manipulation, lower cost, and conservative nature continue to recommend composite resins for smaller cavities and less critical areas. Clinical context, patient considerations, and functional requirements should therefore influence the choice of material. Additional clinical studies with follow-up of several years' duration are suggested to confirm these in vitro findings and guide further, more specific material guidelines in restorative and prosthetic dentistry.

DECLARATION

Ethical Approval: This study was approved by the Institutional Ethics Committee. This study was conducted in accordance with the principles of the Declaration of Helsinki regarding ethical research involving human sub jects.

Informed Consent: Written informed consent was obtained from all participants prior to enrollment.

Availability of Research Data: All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding or Financial Support: The authors declare that no external funding or financial assistance was received for the conduct of this research.

Conflict of Interest Statement: The authors declare no conflicts of interest related to this study.

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