Keywords
Restorative materials, Clinical performance, Longevity, Bioactive materials, Dental composites

Authors

Dr. Ena Maakhni[1*]
Senior Resident, Department of Dentistry Specialization in Conservative Dentistry and Endodontics, AIIMS Gorakhpur,
Email Id: emaakhni@gmail.com, Orcid Id: 0009-0002-9605-3889

Dr Sushmita Pattnaik[2]
Assistant Professor, Department of Dentistry, Government Medical College and Hospital Sundargarh, Odisha
University: OUHS
Email Id: sushmita.pattnaik94@gmail.com,
Orcid Id: 0009-0005-9459-9193

Dr Mujahid Ahmed[3]
Reader, Department of Conservative dentistry and Endodontics Sri Siddhartha Dental College Sri Siddhartha Academy of Higher Education, B.H. Road, Agalakote , Tumkur- 572107
Email Id: ahmedahmed.sheik@gmail.com
Orcid Id: 0000-0001-8180-6994

Viswanathan Kaliyaperumal[4]
Department of Prosthodontics
Saveetha Dental College and Hospital
Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai-600 077, India
E-mail Id: viswanathanphd@yahoo.com
Orcid id: 0000-0003-2800-9739

Dr Stuti Gupta[5]
Associate Professor, Department of Periodontology, School of dental Sciences, Sharda University,
Email Id:stutigupta0901@gmail.com,
Orcid Id: 0000-0001-8495-8723

Megha Das[6]
Intern, BDS, Department of Dental, Kalinga Institute of Dental Sciences
Bhubaneswar, Pin code: 751024, India,
Orcid Id: 0009-0006-6849-9372
Email Id: mdas52149@gmail.com

Address for correspondence: Dr. Ena maakhni
Senior Resident, Department of Dentistry Specialization in General Dentistry
AIIMS Gorakhpur.
Email Id: emaakhni@gmail.com
Orcid Id: 0009-0002-9605-3889

Received:27-06-2026
Revised:05-08-2026
Accepted:10-08-2026
Doi:10.1922/ejprd.v34i7s.1751

European Journal of Prosthodontics and Restorative Dentistry (2026) 34(7s), 1123–1130

Advances in Restorative Dental Materials: A Comprehensive Evaluation of Clinical Performance and Longevity

Abstract
Restorative dental materials have evolved significantly, driven by increasing demands for durability, aesthetics, and biological compatibility. This review aims to comprehensively evaluate the clinical performance and longevity of contemporary restorative materials, including direct, indirect, and emerging bioactive systems. A structured literature review was conducted using major databases, focusing on clinical studies, systematic reviews, and recent advancements in material science. Findings indicate that modern materials such as resin composites, ceramics, and CAD/CAM hybrids demonstrate improved mechanical properties, adhesion, and aesthetic outcomes compared to traditional materials. However, factors such as polymerization shrinkage, hydrolytic degradation, and secondary caries continue to affect long-term performance. Bioactive and smart materials show promising potential in enhancing remineralization, reducing bacterial activity, and improving restoration durability. Clinical longevity is influenced not only by material properties but also by operator skill, clinical protocols, and patient-related factors. Despite substantial progress, limitations in long-term clinical evidence and variability in evaluation methods persist. Future research should focus on standardized methodologies and long-term trials to strengthen evidence-based practice. The integration of advanced materials with optimized clinical strategies is essential for achieving predictable and sustainable restorative outcomes.

1. INTRODUCTION

The field of restorative dentistry has experienced some dramatic changes during the last few decades, moving from the use of amalgam and traditional restoration methods to adhesive technology and biologically active materials [1]. At first, the process of tooth restoration was oriented at the duration and efficiency of restorations; however, biomimetics and aesthetics, as well as minimally invasive treatment, which makes it possible to imitate the structure and functions of the natural tooth, were added to the list of restorative dentistry [2]. Additionally, recent discoveries in dental materials and regenerative dentistry have influenced the development of restorative practices and initiated a new epoch when dental materials became available for practical use [3].

Currently, there is a need for materials with high durability and aesthetic qualities. Patients and dentists seek long-lasting restorations that look natural, do not wear out, and preserve their color while remaining functional for a long period of time [4]. Besides, apart from the innovations introduced by new materials like CAD/CAM system, one more reason why restorations have become more aesthetic and mechanically durable lies in the introduction of new materials [5].

Despite all these developments, there have been a number of issues that are posing a threat to the effectiveness of the dental restoratives over time. One of the major issues is the occurrence of secondary caries, which is associated with factors such as microleakage and biofilm degradation of the tooth-restoration interface [6]. Other issues, such as shrinkage, fatigue, wear, and chemical degradation, should also be noted. The occurrence of such multidisciplinary issues shows how difficult it is to provide sustainable and consistent dental restorations.

Although almost all restoratives have been extensively investigated, there are still no findings regarding the comparative efficacy and long-term use of these materials (Figure 1). Literature is focused on the investigation of one restorative type or their short-term influence on dental health to create a research gap for the effectiveness of these materials. Therefore, the goal of the review is to conduct an evaluation of the achievements made in restorative dental materials.

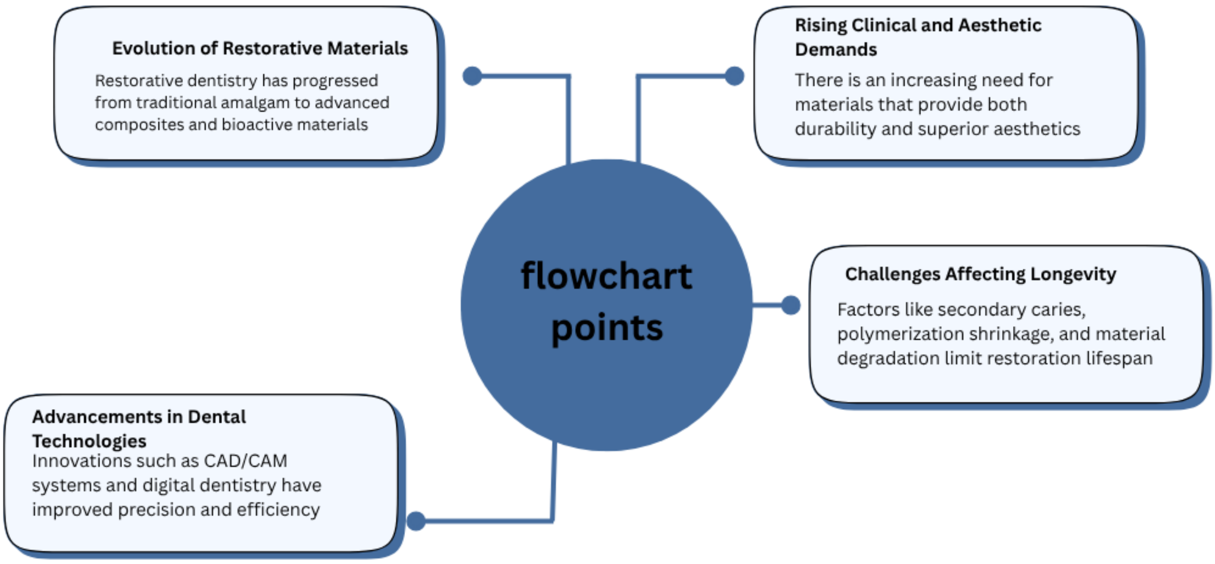

Figure 1: Conceptual Framework of Advances and Challenges in Restorative Dental Materials

This flowchart illustrates the progression of restorative dental materials, highlighting evolving clinical demands, technological advancements, and key challenges affecting longevity. It emphasizes the need for improved materials that balance durability, aesthetics, and long-term clinical performance in modern dentistry.

OBJECTIVES

1. To evaluate the clinical performance and longevity of current restorative dental materials
2. To compare key properties influencing survival outcomes across different material types
3. To analyze recent advancements in restorative materials and their impact on clinical success

2. METHODOLOGY

This was in the form of a structured narrative review with systematic search components as per PRISMA guidelines. PubMed, Scopus, Web of Science, and Cochrane Library were thoroughly searched to identify the studies published between 2010 and 2025 using the following relevant keywords and MeSH terms restorative dental materials, clinical performance and longevity. Eligible studies were limited to clinical trials, cohort studies, and systematic reviews that were published in English whereas in vitro studies, case reports, and irrelevant articles were excluded. The selection of studies was conducted based on title, abstract, and full-text screening by the independent reviewers. The characteristics of the studies, the type of materials used, and the clinical outcomes were extracted and analyzed. Quality evaluation was conducted with common risk-of-bias instruments and since the results were heterogeneous, the synthesis was conducted qualitatively to compare their performance patterns and durability with the materials.

3. CLASSIFICATION OF RESTORATIVE DENTAL MATERIALS

3.1 Direct Restorative Materials

Direct restorative materials are commonly used as they are conservative, cost-effective, and can be placed at the chairside. Following their better aesthetic qualities and increased mechanical performance, composite resins such as microhybrid, nanofilled, and bulk-fill types, have emerged as the material of choice in modern dentistry. Filler technology has improved the wear resistance, compressive strength, and polishability, which allows it to be used for both anterior and posterior restorations. However, both GICs and RMGICs continue to be clinically important in relation to the ability to provide fluoride release and adhesive properties. The introduction of new products such as EQUIA Forte has demonstrated clinical superiority in relation to compressive strength and surface microhardness compared to traditional glass ionomer and has continued to demonstrate its importance clinically [7].

Dental amalgam, despite its initial stability and affordability, is being gradually phased out worldwide due to health and environmental implications associated with the presence of mercury in it. While it demonstrates good longevity and wear resistance, there has been a decline in its use because other materials are now gaining more attention [8].

3.2 Indirect Restorative Materials

The indirect restorative materials are fabricated out of the mouth and bonded or cemented, which offers the optimum mechanical characteristics and precision. Feldspathic ceramics, leucite-reinforced ceramics, lithium disilicate, and zirconia, have been in the limelight because of their superior aesthetics, biocompatibility and strength. Recent systematic data reveals that lithium disilicate and zirconia-based restorations show high survival rates and good complication rates especially in veneer and full-coverage restorations [9].

Though less prevalent in the aesthetic dentistry application, metal alloys still offer unparalleled strength and durability in high load bearing applications. They have however deteriorated as more patients are opting to use metal free restorations [10]. Meanwhile, the CAD/CAM technology has relegated restorative dentistry to a whole new level of precision, allowing the creation of highly precise restorations with the help of hybrid materials, which are a combination of the ceramic and polymer properties. These composite CAD/CAM materials have desirable mechanical characteristics such as increased fracture resistance and elastic modulus which adds to better clinical performance [11].

3.3 Emerging and Bioactive Materials

Overcoming deficiencies of the traditional restorative material along with replicating the biological features of natural dental structures has become the motivation for developing new restorative materials. In addition, another important advancement is represented by bioactive composites that are capable of releasing ions, such as calcium and phosphate ions, which contribute to remineralization and inhibit secondary caries. These capabilities have been greatly enhanced due to the implementation of nanotechnology that allows the interaction of composite with oral cavity [12].

The concept of sensitive dental materials, especially the materials that are sensitive to environmental conditions, such as changes in pH, was found to be quite effective in combating caries. In particular, they are able to deliver antibacterial compounds or remineralization ions under acidic conditions [13].

Finally, in terms of their structure and functions, both biomimetic and regenerative approaches are going to imitate natural dental tissues [14]. The materials should be biocompatible and be adapted to biological conditions so as to enable the restoration and stability of restorations over a long period. Biomimetics in restorative dentistry can be considered a revolution in dental practice [15].

Table 1. Classification of Restorative Dental Materials

Category	Examples	Key Features	Clinical Relevance	References
Direct restorative materials	Composite resins	Esthetic, adhesive, versatile	Commonly used for anterior and posterior restorations	[1]
	GIC, RMGIC, EQUIA Forte	Fluoride release, chemical adhesion, improved hardness	Useful in pediatric, cervical, and high-caries-risk cases	[7]
	Dental amalgam	Durable, wear-resistant, cost-effective	Historically important, now under phase-down	[8]
Indirect restorative materials	Feldspathic, lithium disilicate, zirconia ceramics	High esthetics, strength, biocompatibility	Preferred for veneers, crowns, and esthetic restorations	[9]
	Metal alloys	High strength and longevity	Used in stress-bearing areas, less favored esthetically	[1]
	CAD/CAM hybrid materials	Precision fit, favorable mechanical behavior	Important in digital restorative dentistry	[10,11]
Emerging materials	Bioactive composites	Ion release, remineralization potential	Promising for secondary caries prevention	[12]
	Smart materials	pH-responsive, antibacterial action	Potential for targeted caries control	[13]

	Biomimetic materials	Mimic natural tooth structure and function	Support regenerative and conservative dentistry	[14,15]

4. KEY DETERMINANTS OF CLINICAL PERFORMANCE

The clinical performance and longevity of restorative dental materials is a complex interaction involving mechanical, physical, chemical, adhesive, biological, aesthetic aspects. Strength, fracture toughness and fatigue resistance are some of the mechanical properties that are important in the ability to sustain functional occlusal forces and structural failure, wherein reinforced composites have shown better fracture and fatigue resistance [16]. The physical properties are also essential since shrinkage of polymerization of resin-based materials can lead to the occurrence of marginal spaces and microleakage, whereas variations in thermal expansion coefficients between restorative material and tooth structure can lead to interfacial stresses during temperature variations [17,18]. Moreover, wear resistance is critical to retain occlusal integrity in the long run. Chemical stability also influences the life cycle, with hydrolytic wear of the material structure, filler interface, and surface damage potentially influencing structural integrity, and plaque formation and aesthetic loss [19,20]. The strength and stability of the bond is also mandatory and enamel provides a more predictable bonding surface compared to dentin where moisture and organic characteristics complicate adhesion; the retention of the hybrid layer has a considerable contribution to bond failure in the long term despite the enhanced adhesive systems [21,22,23]. Biologically, restorative materials have to be highly biocompatible, and preferably, antibacterial to reduce biofilm and secondary caries, and the latest restorative materials like chitosan-based systems have shown potential [24]. Lastly, aesthetic performance such as color stability, translucency and polish retention of the surface are critical to patient satisfaction but may be negatively influenced by chemical and mechanical degradation with time [20]. All of these determinants emphasize that restorative material performance is multifactorial and requires materials that provide an optimum balance of all properties to be long-term clinical success.

Table 2. Clinical Longevity and Performance of Restorative Materials

Parameter	Key Findings	Clinical Implication	References
Survival rates	Vary by material type and clinical application; generally high for modern materials	Indicator of long-term clinical success	[25]
Failure modes	Fracture, marginal leakage, secondary caries are most common	Need for improved material properties and sealing ability	[25]
Amalgam vs composite (posterior)	Comparable longevity; amalgam slightly superior in long-term durability	Composite preferred for esthetics despite technique sensitivity	[26]
Anterior restorations	High survival rates for composite restorations	Suitable for esthetic zones with proper technique	[27]
Ceramic restorations	High survival and low complication rates (veneers, crowns)	Preferred for long-term esthetic restorations	[28]
Anterior vs posterior performance	Posterior restorations show higher failure rates due to occlusal load	Material selection must consider load-bearing क्षमता	[25]
Operator factors	Skill, technique, and cavity design significantly affect outcomes	Emphasis on clinical training and protocol adherence	[29]
Patient-related factors	Oral hygiene, occlusion, diet influence longevity	Personalized treatment planning required	[30]

6. ADVANCES IN MATERIAL TECHNOLOGIES

6.1 Nanotechnology in Restorative Materials

Nanofilled and nanohybrid composite which has superior mechanical and functional characteristics have been developed with the introduction of nanotechnology in restorative dentistry (Figure 2). These materials are highly fracture resistant, wear resistant and retain polish since the distribution of fillers is optimized and filler loading is increased. Nanoscale interaction between fillers and resin matrix also leads to a better mechanical stability and less surface degradation, thus, increasing long-term clinical performance.

6.2 CAD/CAM and Digital Dentistry Integration

Digital dentistry technology, in particular CAD/CAM and 3D printing technologies, revolutionized the process of restoration workflow design and implementation. Due to the use of such technologies, a high-quality restoration is possible due to the increased margin accuracy and higher reproduction rate of the restoration, in addition to reducing chairside time. Minimally invasive preparation is done using digital tools and allows for customization of restoration according to the needs of each individual patient [31].

6.3 Bioactive and Remineralizing Systems

An active reaction to the oral environment is being identified as one of the major growth points for bioactive restorative materials. These materials emit therapeutic ions, including calcium and phosphate, which promote the remineralization process of enamel and prevent the demineralization process [32]. Bioactive glasses and glass ionomers have shown high efficiency in remineralization and prevention of secondary caries, hence increasing longevity in the restorations [33]. They can help achieve ionic equilibrium in a positive manner, thus providing better performance and longevity.

6.4 Self-healing and Smart Materials

Intelligent and self-healing materials are considered to be a proactive continuation of restorative dentistry that responds to the changes in the environment, such as pH levels and physical stress. Healing of micro-cracks occurs because of the healing elements that the material contains, as well as through chemical bonds that can break and form again. Moreover, intelligent materials may respond with antibacterial or remineralizing qualities to an acidic environment. The potential applications of smart materials are quite large in terms of increasing the service period of restorations [34].

Figure 2: Technological Innovations in Contemporary Restorative Dental Materials

This figure highlights key advancements in restorative material technologies, including nanotechnology, digital CAD/CAM systems, bioactive materials, and smart self-healing systems. These innovations collectively enhance mechanical strength, precision, biological interaction, and long-term clinical performance of dental restorations.

7. CLINICAL PERFORMANCE IN SPECIFIC APPLICATIONS

7.1 Posterior Restorations

Due to the posterior restoration carrying occlusal loads, the longevity factors would involve mechanical properties, wear resistance, and marginal adaptation. The materials used for posterior restorations include resin composite material and glass ionomer cements, but their longevity is affected by polymerization shrinkage, fatigue, and secondary caries. Bioactive dental materials have shown promising results when applied in posterior applications, releasing calcium and phosphate ions to remineralize and reduce the possibility of secondary caries development [33,35].

7.2 Anterior Aesthetic Restorations

Anterior restorations are also more concerned with aesthetics and functional performance, although the stability of the color, translucency and surface finish are the primary criteria. The direct composite restoration and the ceramic systems are commonly applied due to their superior optical qualities. Anterior composite restorations have been shown to have good survival rates when adhesive guidelines are adhered to but long-term survival may be affected by surface decay and discoloration [27]. The aesthetic durability and resistance to staining of materials have been enhanced by the continual development of materials.

7.3 Pediatric Dentistry

Restorative materials used in the field of pediatric dentistry must meet some of the requirements such as ease of use, release of fluoride and biocompatibility. Glass ionomer cements and their derivatives are often used because of their cariostatic and chemical bonding. Moreover, the adjunctive technology such as lasers have also promoted minimally invasive treatment procedures, discomfort and clinical outcomes in patients [36]. The caries prevention and enamel remineralization of the pediatric population is also contributed by bioactive materials.

7.4 Geriatric and High-risk Patients

Other issues, including a reduction of the salivary flow, a predisposition to root caries, and poor oral hygiene, are unique to geriatric and high-risk patients and their challenges of restorative treatment. In such cases, preference of materials which have been enhanced in terms of biological properties such as antibacterial action and possible ion release which would improve clinical outcomes is favored. Bioactive restorative systems are an important factor preventing the occurrence of secondary caries and preserving restoration integrity in such populations [35]. Additionally, the adequate clinical performance norms that must be achieved need to be established by ensuring that restorative materials can cater to the specific needs of patients that are at a high risk [37].

7.5 Role of Smart and Advanced Materials Across Applications

In any clinical setting, combination of smart and self-healing materials has brought forth new opportunities in enhancing restorative performance. These materials are able to react to environmental influences, repair microstructural injuries and have antibacterial properties, thus increasing durability and dependability across various patient groups [34]. These innovations reflect the trend in the direction of individualized and functional-adaptive restorative approaches of contemporary dentistry.

8. LIMITATIONS OF CURRENT EVIDENCE

Despite the fact that much has been done in the area of restorative dental materials, the evidence available has several limitations that can restrict conclusive results in the area of their long-term clinical performance and excellence. The heterogeneity of clinical studies is among one of the greatest obstacles as it entails the difference in study design, sample size, length of follow-up, and types of the materials, making it difficult to directly compare and synthesize the findings of the studies. Also, long-term clinical data, particularly since 10 years ago, of many current materials, such as bioactive and clever systems, is highly lacking, thus limiting the ability to quantitatively assess their long-term survival and durability. The discrepancies in the documented results can also be attributed to the inconsistency in the evaluation criteria as different studies employ different methods in the evaluation of parameters such as the failure rates, marginal adaptation and aesthetic performance. Moreover, publication bias still remains as positive results are more likely to be published rather than studies that obtain negative or inconclusive results and may bias the overall evidence base. These limitations lead to the need to have standardized procedures, long term randomized clinical trials and reporting protocols to strengthen the evidence and add to the evidence-based decision making in restorative dentistry.

9. FUTURE DIRECTIONS AND RESEARCH PRIORITIES

Regarding the innovations in materials used for restorations, there needs to be a look into the inadequacies in the clinical studies carried out thus far and the need to enhance the reliability of the procedures. The main thing to be done would be to ensure that there are universal guidelines for clinical studies that could enable one to compare the results more effectively. In addition, there is need for long-term clinical trials that would give accurate results on the longevity of both conventional and innovative restoratives.

The integration of artificial intelligence (AI) and digital monitoring technologies is a promising area of advancement in restorative dentistry. AI can be helpful in designing a treatment plan, selecting restorative material, and detecting failure at an early stage, whereas digital monitoring can assist in monitoring the integrity of restorations and risk factors unique to the patient. Furthermore, research must be devoted to the development of completely biomimetic materials, similar to the structural, mechanical and biological properties of natural tooth tissues. The materials have the ability to accelerate tissue integration, regeneration and extend the longevity of restorations significantly. Combined, these research priorities will be the key to more evidence-based restorative dentistry and more sustainable and patient-centered clinical outcomes.

10. CLINICAL IMPLICATIONS

The clinical performance, longevity and patient specific needs should inform the choice of restorative dental materials. The evidence-based approach to the choice of the materials in the restoration is critical because of the location of the restoration, functional load, aesthetic needs, and profile of the caries risk of a patient. As an example, posterior restorations need to be made of highly strong and wear-resistant material, but anterior restorations need to be made of high-quality aesthetics, including the color stability and translucency.

An organized decision-making model that entails material properties, clinical conditions and operator expertise should also be considered by the clinicians. The correct choice of cases, compliance with clinical guidelines, and the application of the correct adhesive methods are important to achieve the highest rates of restoration success and the minimum rates of failures. In addition, oral care, nutrition, and occlusional habits are among the patient-specific factors necessary to incorporate into the treatment plan to make it long-term.

Cost-efficiency is another factor which should be taken into account in the clinical practice. Even though the newer materials like the CAD/CAM ceramic or bioactive materials might have more benefits from the perspective of effectiveness and durability, the price of the materials might be too expensive for some people. For that reason, doctors should find a good balance between the benefits of the materials and their price. All in all, scientific information combined with the right clinical decisions will be crucial for achieving long-lasting outcomes.

11. CONCLUSION

Innovation in the field of restorative dental materials has tremendously contributed to the functionality and aesthetics of contemporary dentistry. In other words, today's contemporary dental materials such as resin composites, ceramic materials, CAD/CAM hybrid materials, and bioactive materials are much better in terms of mechanical performance compared to their traditional counterparts. However, the durability of the dental restorations cannot be solely attributed to the characteristics of the materials used; in fact, it is based on an interaction between various components including material adhesion stability, technical and clinical proficiency and even patients' factors such as their dental health and occlusal stresses. Though these materials can achieve high success rates, there are certain issues limiting their performance. There has been great optimism in bioactive and smart materials in the quest for solutions since they are capable of remineralization, capable of acting as antibacterial materials, and able to monitor the oral environment that may eventually lead to increased longevity of restorations. The main challenge is that there is a lack of convincing clinical evidence on most of these materials in the long term. Thus, future research should be conducted using standardized protocols for evaluation and clinical testing. Finally, it is important to consider the evidence-based and patient-centered approach when choosing biomaterials alongside good clinical practices.

REFERENCES

1. Singh, H., Kaur, M., Dhillon, J. S., Mann, J. S., & Kumar, A. (2017). Evolution of restorative dentistry from past to present. Indian Journal of Dental Sciences, 9(1), 38-43.
2. Paryani, M., Bhojwani, P. R., Ikhar, A., Reche, A., & Paul, P. (2023). Evolution of biomimetic approaches for regenerative and restorative dentistry. Cureus, 15(1).
3. Orsini, G., Tosco, V., Monterubbianesi, R., Orilisi, G., & Putignano, A. (2020). A new era in restorative dentistry. The First Outstanding 50 Years of "Università Politecnica delle Marche" Research Achievements in Life Sciences, 319-334.
4. Emma, O., & Harris, F. (2024). Material Innovations in CAD/CAM Restorations: Assessing the Impact of Advanced Dental Materials on Aesthetics, Longevity, and Economic Viability.
5. Alshehri, Z. A., Alqahtani, S. A., & Alzahrani, F. A. (2024). Evaluation of longevity and performance of various dental filling materials. J Healthc Sci, 4, 690-696.
6. Carrera, C. A., Li, Y., Chen, R., Aparicio, C., Fok, A., & Rudney, J. (2017). Interfacial degradation of adhesive composite restorations mediated by oral biofilms and mechanical challenge in an extracted tooth model of secondary caries. Journal of Dentistry, 66, 62-70.
7. Poornima, P., Koley, P., Kenchappa, M., Nagaveni, N. B., Bharath, K. P., & Neena, I. E. (2019). Comparative evaluation of compressive strength and surface microhardness of EQUIA Forte, resin-modified glass-ionomer cement with conventional glass-ionomer cement. Journal of Indian Society of Pedodontics and Preventive Dentistry, 37(3), 265-270.
8. Kisumbi, B. K., Osiro, O. A., Gathece, L. W., & Maina, S. W. (2025). Dental Amalgam Phase-Down—Status, Alternatives, Strategies and Preparedness for Implementation: A Review. International Journal of Dentistry, 2025(1), 6688410.
9. Klein, P., Spitznagel, F. A., Zembic, A., Prott, L. S., Pieralli, S., Bongaerts, B., ... & Gierthmuehlen, P. C. (2025). Survival and complication rates of feldspathic, leucite-reinforced, lithium disilicate and zirconia ceramic laminate veneers: A systematic review and meta-analysis. Journal of Esthetic and Restorative Dentistry, 37(3), 601-619.
10. Palacios, T., Tarancón, S., & Pastor, J. Y. (2022). On the mechanical properties of hybrid dental materials for CAD/CAM restorations. Polymers, 14(16), 3252.
11. Horvath, S. D. (2016). Key Parameters of Hybrid Materials for CAD/CAM-Based Restorative Dentistry. Compendium of continuing education in dentistry (Jamesburg, NJ: 1995), 37(9), 638-643.
12. Zhao, Y., Zhang, Z., Pan, Z., & Liu, Y. (2021, December). Advanced bioactive nanomaterials for biomedical applications. In Exploration (Vol. 1, No. 3, p. 20210089).
13. Yu, K., Zhang, Q., Dai, Z., Zhu, M., Xiao, L., Zhao, Z., ... & Zhang, K. (2023). Smart dental materials intelligently responding to oral pH to combat caries: a literature review. Polymers, 15(12), 2611.
14. Singer, L., Fouda, A., & Bourauel, C. (2023). Biomimetic approaches and materials in restorative

and regenerative dentistry. BMC oral health, 23(1), 105.
15. Suhag, D., Kaushik, S., & Taxak, V. B. (2024). Biomimetic materials. In Handbook of Biomaterials for Medical Applications, Volume 1: Fundamentals (pp. 247-269). Singapore: Springer Nature Singapore.
16. Bijelic-Donova, J., Garoushi, S., Vallittu, P. K., & Lassila, L. V. (2016). Mechanical properties, fracture resistance, and fatigue limits of short fiber reinforced dental composite resin. The Journal of prosthetic dentistry, 115(1), 95-102.
17. Kaisarly, D., & Gezawi, M. E. (2016). Polymerization shrinkage assessment of dental resin composites: a literature review. Odontology, 104(3), 257-270.
18. Somano, T. T. (2022). The Physical Properties of Thermal Expansion of Solid Matter. American Journal of Modern Physics, 11(5), 79-84.
19. Tsuji, H. (2022). Hydrolytic degradation. Poly (Lactic Acid) Synthesis, Structures, Properties, Processing, Applications, and End of Life, 467-516.
20. Lemos, C. A., Mauro, S. J., Dos Santos, P. H., Briso, A. L., & Fagundes, T. C. (2017). Influence of mechanical and chemical degradation in the surface roughness, gloss, and color of microhybrid composites. The Journal of Contemporary Dental Practice, 18(4), 283-288.
21. Frassetto, A., Breschi, L., Turco, G., Marchesi, G., Di Lenarda, R., Tay, F. R., ... & Cadenaro, M. (2016). Mechanisms of degradation of the hybrid layer in adhesive dentistry and therapeutic agents to improve bond durability—A literature review. Dental Materials, 32(2), e41-e53.
22. Latta, M. A., Tsujimoto, A., Takamizawa, T., & Barkmeier, W. W. (2020). Enamel and dentin bond durability of self-adhesive restorative materials. J. Adhes. Dent, 22(1), 99-105.
23. Alomran, W. K., Nizami, M. Z. I., Xu, H. H., & Sun, J. (2025). Evolution of dental resin adhesives—a comprehensive review. Journal of Functional Biomaterials, 16(3), 104.
24. Wu, C. S., Hsu, Y. C., Liao, H. T., & Cai, Y. X. (2015). Antibacterial activity and in vitro evaluation of the biocompatibility of chitosan-based polysaccharide/polyester membranes. Carbohydrate polymers, 134, 438-447.
25. Fernandes, N. A., Vally, Z. I., & Sykes, L. M. (2015). The longevity of restorations-A literature review. South African Dental Journal, 70(9), 410-413.
26. Moraschini, V., Fai, C. K., Alto, R. M., & Dos Santos, G. O. (2015). Amalgam and resin composite longevity of posterior restorations: A systematic review and meta-analysis. Journal of dentistry, 43(9), 1043-1050.
27. Heintze, S. D., Rousson, V., & Hickel, R. (2015). Clinical effectiveness of direct anterior restorations—A meta-analysis. Dental materials, 31(5), 481-495.
28. Alghazzawi, T. F. (2024). Clinical survival rate and laboratory failure of dental veneers: a narrative literature review. Journal of functional biomaterials, 15(5), 131.
29. Marquardt, S., Rodt, T., Rosenthal, H., Wacker, F., & Meyer, B. C. (2015). Impact of anatomical, procedural, and operator skill factors on the success and duration of fluoroscopy-guided transjugular intrahepatic portosystemic shunt. Cardiovascular and interventional radiology, 38(4), 903-912.
30. Doğramacı, E. J., & Rossi-Fedele, G. (2023). Patient-related outcomes and oral health-related quality of life in endodontics. International Endodontic Journal, 56, 169-187.
31. Alaoffey, A. S., Asiri, M. A., Alhazmi, T. A. A., Alshetaiwi, A. A., Almobarak, A. M., Alqasir, Y. H., ... & Alharbi, F. N. (2024). Digital dentistry: transforming diagnosis and treatment planning through CAD/CAM and 3D printing. Egyptian Journal of Chemistry, 67(13), 1177-1190.
32. Farjaminejad, R., Farjaminejad, S., Garcia-Godoy, F., & Jalali, M. (2025). The Role of Bioactive Glasses in Caries Prevention and Enamel Remineralization. Applied Sciences, 15(24), 13157.
33. Tuygunov, N., Khairunnisa, Z., Yahya, N. A., Aziz, A. A., Zakaria, M. N., Israilova, N. A., & Cahyanto, A. (2024). Bioactivity and remineralization potential of modified glass ionomer cement: A systematic review of the impact of calcium and phosphate ion release. Dental Materials Journal, 43(1), 1-10.
34. Kontiza, A., & Kartsonakis, I. A. (2024). Smart composite materials with self-healing properties: A review on design and applications. Polymers, 16(15), 2115.
35. Sonbul, H. M. (2025). Influence of bioactive restorative materials on secondary caries prevention: a clinical and in vitro study. Journal of Pharmacy and Bioallied Sciences, 17(Suppl 2), S1787-S1789.
36. Nazemisalman, B., Farsadeghi, M., & Sokhansanj, M. (2015). Types of lasers and their applications in pediatric dentistry. Journal of lasers in medical sciences, 6(3), 96.
37. Lord, S. J., St John, A., Bossuyt, P. M., Sandberg, S., Monaghan, P. J., O'Kane, M., ... & Test Evaluation Working Group of the European Federation of Clinical Chemistry and Laboratory Medicine. (2019). Setting clinical performance specifications to develop and evaluate biomarkers for clinical use. Annals of clinical biochemistry, 56(5), 527-535.