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Bioactive restorative materials, Pediatric dentistry, Dental caries, Remineralization, Minimally invasive dentistry

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# Clinical Effectiveness of Bioactive Restorative Materials in Pediatric Dental Caries Management

**Abstract**
Pediatric dental caries remains a major global health concern, necessitating effective restorative strategies that not only restore tooth structure but also support disease control and prevention. Bioactive restorative materials have emerged as a promising alternative to conventional materials due to their ability to interact dynamically with dental tissues and the oral environment. This review aims to evaluate the clinical effectiveness of bioactive restorative materials in pediatric dental caries management and to assess their therapeutic advantages in contemporary practice. Bioactive materials, including glass ionomer cements, resin-modified glass ionomers, giomers, bioactive composites, and calcium silicate-based materials, demonstrate properties such as fluoride, calcium, and phosphate ion release, remineralization potential, antibacterial activity, and pulp-protective effects. Clinical evidence suggests that these materials may enhance restoration longevity, reduce secondary caries, improve marginal integrity, and support minimally invasive treatment approaches. However, their performance varies depending on material composition, clinical conditions, and patient-related factors. Despite promising outcomes, current evidence is limited by heterogeneity in study designs and a lack of long-term pediatric-specific clinical trials. Therefore, careful material selection based on individual clinical needs is essential. Further high-quality research is required to establish standardized guidelines and optimize the role of bioactive restorative materials in pediatric dentistry.

## 1. Introduction

Pediatric dental caries remains one of the most prevalent chronic diseases affecting children worldwide and continues to represent a substantial clinical and public health burden (Figure 1). Although significant advances have been made in the area of preventive dentistry, the prevalence of untreated caries in primary and young permanent teeth continues to be a common occurrence especially in low and middle-income environments and in the disadvantaged groups in the society [1]. Dental caries among children is not only limited to localized destruction of the tooth, but in most cases, lead to pain, infection, eating difficulty, disturbed sleep, speech disabilities, poor academic performance in school and also low quality of life. Moreover, the widespread caries disease in childhood presents a long-term family and healthcare burden, which is why restorative treatment methods are highly desirable and should be not only effective but also preventive and biologically supportive [2].

Pediatric dental caries is also a significant problem in nations like India where alterations in diets, ineffective practices in oral hygiene, low levels of awareness, and poor access to oral health services persist in contributing to the high incidence of the disease [2]. Children tend to present in such settings with advanced lesions that demand restorative intervention at very early age. Since caries in children are sensitive to fast progression because of the morphological and structural features of the primary teeth, it is critical to manage it in time and adequately. This scenario reveals the significance of restorative substances that can be used safely in the pediatric oral cavity and help to manage the further evolution of the disease and avoid the recurrence in the future.

The use of restorative therapy among children presents special

issues as opposed to treating adults. Children are characterized by poor cooperation, anxiety, attention, poor tolerance of long or technique sensitive procedures. Also, the primary teeth have less enamel and dentin, their pulp chambers are relatively large, and they contain fewer minerals, which makes them susceptible to the rapid development of caries and pulpal involvement [3]. The problem of moisture control is often a challenge when dealing with young children especially when making posterior restorations and such a factor may hamper the workability of materials that require that they operate under dry conditions. As a result, the factor of restorative success in pediatric dentistry is not only in the intrinsic character of the material but equally in the ease of handling, biocompatibility, therapeutic potentiality, and clinical flexibility of less-than-optimal conditions [4].

Traditional restorative products like amalgam, composite resin, compomer and traditional glass ionomer cement have been extensively used in pediatrics. Nonetheless, there are some limitations of each of these materials. Composite resin has better esthetics and desirable mechanical qualities, but is very technique sensitive and needs careful moisture control [5]. Traditional glass ionomer cements contain an ability to release fluoride and adhesion to tooth structure as well as mechanical strength and wear resistance, which might not be sufficient in stressful locations. The network meta-analysis demonstrates that no traditional material can be viewed as the best when it comes to all posterior primary tooth restorations, meaning that more versatile and bioactivity-based options should be developed [3].

During the recent years, bioactive restorative materials have become a significant part of the innovation in the field of pediatric dentistry. Bioactive materials do not merely replace lost tooth structure as is the case of conventional materials but rather they are intended to engage dynamically with the dental tissues and the oral environment [4]. As well as, their therapeutic effects can be release of fluoride, calcium, and phosphate ions, remineralization of the adjacent tooth structure, antibacterial effect, enhanced sealing, and pulpal repair. Such characteristics are especially topical in the field of pediatric caries management, where the objectives of treatment become more and more consistent with minimally invasive dentistry, the preservation of tooth vitality, as well as the decrease of secondary prevention of caries [6]. According to modern literature, the introduction of such materials has turned the idea of restorative pediatric dentistry into a more preventive and biologically oriented model of care [7].

New clinical evidence has also supported the use of bioactive restorative materials that are increasingly being used [8]. The recent reviews have reported their possible effectiveness in secondary caries control and enhanced restorative outcomes, but according to the evidence quality, the strongest effect is observed with regard to material classes and clinical conditions [9]. Hence, a critical analysis of their effectiveness in clinical dental caries management among the pediatric population should be conducted. This review seeks to evaluate the existing evidence of bioactive restorative materials in children and determine their role in enhancing the restorative success, remineralization, and current dental care to children [10].

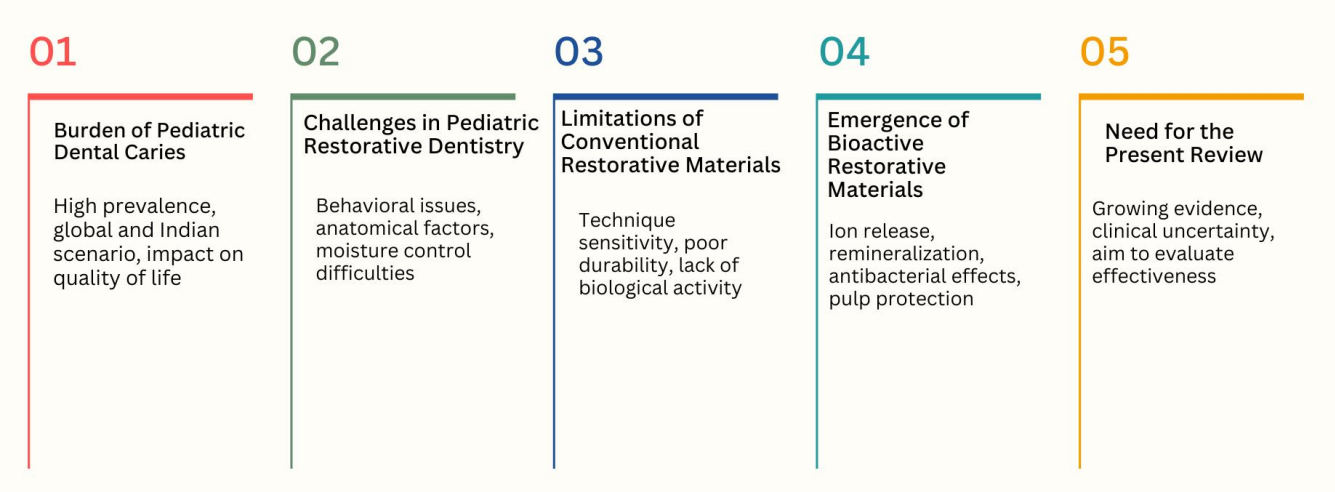


**Figure 1: Conceptual Framework of Bioactive Restorative Materials in Pediatric Caries Management**

This framework outlines the progression from the global burden of pediatric dental caries and clinical challenges to the limitations of conventional materials, highlighting the emergence of bioactive restoratives and the need for evidence-based evaluation in modern pediatric dentistry.

**Objectives**

1. To evaluate the clinical effectiveness of bioactive restorative materials in pediatric dental caries management
2. To compare the performance of bioactive restorative materials with conventional restorative materials in children
3. To assess the role of bioactive restorative materials in remineralization and prevention of secondary caries

## 2. Bioactive Restorative Materials in Pediatric Dentistry

### 2.1 Definition and Concept of Bioactivity

Bioactive restorative materials are a relatively new development in the field of pediatric dentistry since they do not only provide structural substitution of lost tooth tissue, but also interaction with the oral environment (Figure 1). Bioactive materials are also different in that contrary to traditional restorative materials, which are mostly passive, bioactive materials are engineered to generate positive biological responses at the interface of the restoration and the tooth [11]. These effects can be the release of ions (fluoride, calcium, phosphate, and silicate); remineralization promotion; demineralization inhibition; antibacterial effect; and dentin repair or pulpal healing stimulation [12].

The bioactivity concept of restorative dentistry is an inclination of a wider paradigm of changing purely reparative care into biological-based treatment. This method is especially applicable in pediatric patients since managing the caries may need the use of materials that may work under strenuous clinical conditions as well as play a role in the long-term management of the disease. Restorative materials that have preventive and regenerative properties are of significant clinical importance since children are more susceptible to recurrent caries, rapid lesion progression, and pulpal complications [10]. In this way, bioactive materials have been considered to be a part of minimally invasive and preventive pediatric dentistry and not just an alternative to other traditional restorative treatments.

### 2.2 Classification of Bioactive Restorative Materials

It is possible to categorize bioactive restorative material based on their composition, release mechanism of ions and therapeutic effect. One of the most important groups is the materials based on glass ionomers, which has been widely known to release fluoride, bond to enamel and dentin chemically, and cariostatic properties [12]. The resin-modified ion-releasing materials are another group and aim at enhancing mechanical performance and maintaining bioactive potential. Giomers are a unique category of pre-reacted glass technology which can release and recharge fluoride in a resin framework. Bioactive composites have in more recent times been proposed to incorporate aesthetics and strength with remineralizing potential. Moreover, calcium silicate-based products have become significant due to their capacity to encourage the mineralized tissue formation and process pulp therapy [13].

This grouping is clinically significant in pediatric dentistry as each of the groups has unique benefits according to the caries risk, cavity type, moisture management of the child, and restorative needs. The bioactive materials are varied in their use as it is an attempt to make restorative treatment more customized to both functional and biological needs of children [11].

**Table 1: Classification of Bioactive Restorative Materials in Pediatric Dentistry**

| Material Category | Subtypes | Composition | Bioactive Components | Clinical Applications in Pediatric Dentistry | References |
|---|---|---|---|---|---|
| Glass Ionomer Cements (GICs) | Conventional GIC, High-viscosity GIC | Aluminosilicate glass + polyacrylic acid | Fluoride, calcium ions | ART, primary teeth restorations, high caries-risk cases | [10] |
| Resin-Modified Glass Ionomers (RMGICs) | Fuji II LC | GIC + resin (HEMA) | Fluoride | Posterior restorations, liners, moisture-tolerant applications | [12] |
| Giomers | Beautifil II | Resin matrix + PRG fillers | Rechargeable fluoride | Esthetic restorations, Class I & II cavities | [14] |
| Bioactive Composites | Activa BioACTIVE | Resin matrix + bioactive fillers | Calcium, phosphate, fluoride | Esthetic and moderate-load restorations | [8] |
| Calcium Silicate-Based Materials | Biodentine, MTA | Calcium silicate compounds | Calcium ions | Pulp therapy, deep caries management | [13] |

### 2.3 Common Bioactive Restorative Materials Used in Pediatric Dentistry

#### 2.3.1 Glass Ionomer Cements

One of the long-established bioactive restorative materials applied in the field of pediatric dentistry is glass ionomer cements (GICs). Their effectiveness is mostly credited to release of fluoride, adhesion to tooth structure chemically, biocompatibility with the tooth structure and tolerance to moist clinical conditions (Figure 2). They are especially appropriate to be used with children especially in case of cases where total isolation is not possible or minimal invasive treatment is required. GICs are employed in atraumatic restorative therapy and community-based pediatrics due to the convenience and therapeutic effects as well [8].

Although these are the benefits, traditional GICs have constraints especially in fracture toughness, wear strength, and mechanical strength as a whole when

subjected to stressful locations. Thus, they have great value in the pediatric restorative dentistry, but their application has to be matched to the clinical scenario.

### 2.3.2 Resin-Modified Glass Ionomers

Glass ionomer cements (GICs) were modified by resin to overcome the mechanical limitations of the traditional GICs and keep the desirable bioactive properties. The glass ionomers are better handled, have better aesthetics, set faster and have better physical performance by adding the resin components in the glass ionomer matrix. Meanwhile, they retain the capacity to give out fluoride and form a bond with chemically to enamel and dentin [12].

RMGICs are commonly used in the pediatric dentistry where the clinicians need a balance between the therapeutic effect and increased durability. They are also especially handy when it comes to moderate caries activity in children or when time spent on treatment has to be reduced due to their relative ease of placement and greater strength. Consequently, they take a significant role between traditional glass ionomers and more technique-sensitive resin restoratives.

### 2.3.3 Giomers

Giomers are restorative substances on the surface pre-reacted glass ionomer technology, whereby glass fillers are pre-reacted with polyacids, and then placed into a resin structure. This construct allows giomers to integrate the esthetic and mechanical properties of resin-based systems with the release and recharge capacity of fluoride that is found in the glass ionomer systems. They are especially promising in order to replenish fluoride in patients who are at the high risk of recurrent caries and who are of pediatric age [11].

Clinically, giomers have the benefit of being well combined polishable, esthetic, handling, and preventive, which leads to their application in a pediatric restorative care. Their application is particularly pertinent to anterior restorations and children where esthetics is a factor that needs to be evaluated in addition to caries prevention [10].

### 2.3.4 Bioactive Composites

Bioactive composites are a more recent category of restorative material that has been created to address the inherent passive nature of the traditional resin composites. The materials are created to discharge advantageous ions and enhance the process of remineralization without sacrificing the esthetic quality and mechanical strength linked to restorations made of composites. They demonstrate this by their development in line with the requirements of materials that do not just replace the morphology of the tooth, but also actively participate in the caries control and marginal maintenance [11].

Despite the potential of the concept of bioactive composites, its levels of clinical bioactivity and long-term functionality in children are still under research. However, they are a significant trend in remedial material science especially in the case of children, in which recurrent caries is a significant contributor to the failure of restorations.

### 2.3.5 Calcium Silicate-Based Materials

The importance of calcium silicate-based materials in the pediatric dentistry has increased due to the high biological and regenerative nature of calcium silicate materials. These substances give out calcium ions, an alkaline contrivance and trigger mineralized tissue formation, thus they are particularly useful in the treatment of deep caries and essential pulp therapy [13]. They are also unique in their ability to cause the formation of dentin bridges and heal rather than many traditional restorative materials.

Recent advances in the biosilicate cements have increased their applicability in pediatric dentistry where pulp vitality may be a primary treatment goal. They find the application in indirect treatment of the pulp, in pulpotomy and other types of work on deep caries of primary teeth. Their increased application reflects the shift of the field of pediatric dentistry to the strategy that allows to restore not only the tooth structure but also provide biological repair [13].

## 2.4 Clinical Relevance in Pediatric Dentistry

The significance of bioactive restorative materials in pediatric dentistry can be explained by the fact that such materials can be used to match restorative care with preventive and minimally invasive care, as well as with biologically oriented care. Since children often show high activity of caries, impaired cooperation, and increased demand of pulp-preserving treatment, combinations of restoration and ion release, remineralization, and cariostatic activity are especially beneficial. The growing range of materials based on glass ionomers, giomers, bioactive composites, and calcium silicate-based systems has expanded the possibilities of the clinician to choose the materials based on the particular needs of children [8].

Bioactive restorative materials are a major development that has been achieved in management of caries in children. Their classification and increasing clinical uses suggest that they are no longer passive restoration, but rather therapeutic intervention, which reaffirms their increasing presence in the present pediatric dentistry practice.

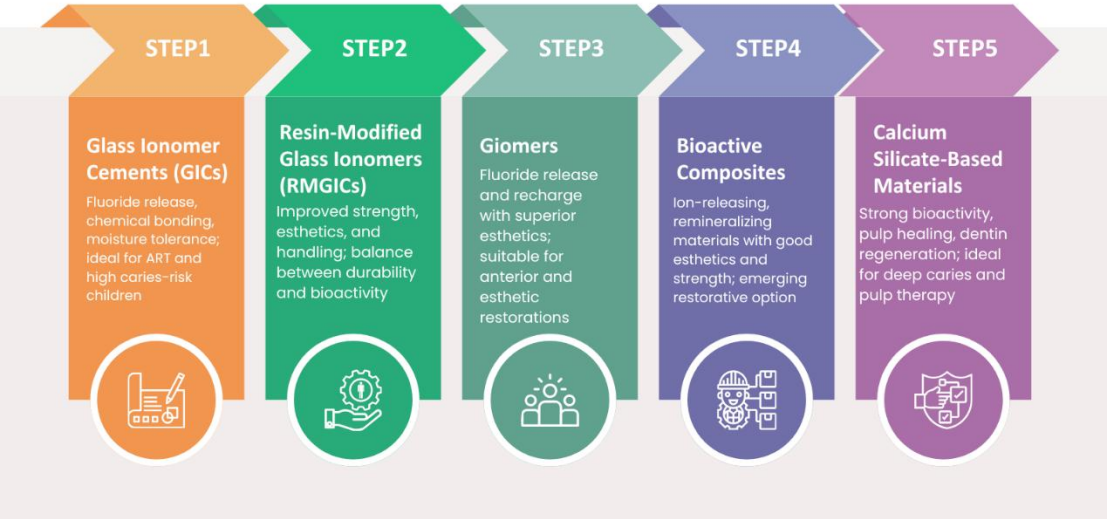


**Figure 2: Classification and Clinical Applications of Bioactive Restorative Materials in Pediatric Dentistry**

This figure illustrates the major categories of bioactive restorative materials used in pediatric dentistry, highlighting their key properties and clinical applications, ranging from fluoride-releasing cements to regenerative calcium silicate materials for minimally invasive and pulp-preserving treatments.

## 3. Mechanisms of Action and Therapeutic Potential

### 3.1 Fluoride, Calcium, and Phosphate Ion Release

Bioactive restorative materials have the following characteristic of releasing therapeutic ions to the adjacent tooth and oral environment. Among these is release of fluoride that is one of the most clinically significant in the dentistry of the pediatrics where children are most susceptible to recurrence of caries and loss of the restoration. Releasing substances of fluoride such as glass ionomer cement, resin-modified glass ionomer cement and giomer have the potential to influence restraining of demineralization, strengthening of the enamel and decreasing cariogenicity at the toothrestoration interface [15]. Particularly of note is giomers, which unlike releasing fluoride, can also be recharged with fluoride and can be the long-term ion reservoirs in the appropriate clinical scenario [14].

Besides fluoride, various bioactive restorative materials also release calcium and phosphate ions, which are critical in the deposition of a mineral and repairing the tooth structure. These ions are able to aid the restoration of mineral balance in the demineralized enamel and dentin and even facilitate development of apatite-like phases on the restoration surface as well as on the surrounding hard tissues. This is especially applicable in teeth of children, where lesions advance at a rapid rate, and the degree of mineral density is relatively low, making it susceptible to structural deterioration. Thus, the release of ions is not a simple chemical process but a treatment process that improves the preventive and restorative effect of such substances [16].

### 3.2 Remineralization Potential

Remineralization potential of bioactive restorative materials is based on the release of fluoride, calcium and phosphate ions. Bioactive materials could be beneficial in the restoration of demineralized enamel and dentin, whereas traditional restorative materials can have no effect beyond that of substituting lost tooth tissue. This is particularly useful in the field of pediatric dentistry where the minimally invasive caries management philosophy focuses on protecting the remaining tooth structure at any cost. These materials can be used in the prevention of progression of lesions by stabilizing partially demineralized tissues by encouraging mineral redeposition [14].

Giomers and materials based on glass ionomers have been of special interest in this aspect since their ion release can produce a local environment in which remineralization can take place. This therapeutic role can have importance, in children with high caries activity, to the restored tooth, as well as to other surfaces that are at risk to cariogenic stress. Therefore, remineralization potential improves the clinical usefulness of bioactive restorative materials by transforming them into active caries control agents [15].

### 3.3 Antibacterial and Anti-Biofilm Effects

Bioactive restorative materials have another significant action mechanism, which is antibacterial and anti-biofilm. In children, restorative material capacity to inhibit the growth of microbees is of great desirability in patients where biofilm formation and eating patterns tend to promote caries development at a very high rate. Bacterial metabolism and acid generation can be suppressed by fluoride release which lowers the cariogenic potential of the plaque biofilm surrounding restoration margin. Certain bioactive materials might also establish alkalinity or release ions that disrupt bacterial adhesion and survival further inhibiting maturation of biofilms [14].

This antimicrobial activity is especially significant in terms of avoiding secondary caries, which has continued to be among the most common reasons of restoration replacement in the pediatric dentistry. Potential solutions to slow down the plaque deposition or biofilm activity are materials that can potentially enhance the duration of restoration and possibly aid in

better disease control with time. Despite the fact that the extent of antibacterial activity depends on the composition, the anti-biofilm capabilities of bioactive materials contribute to their therapeutic importance in the children with a high caries risk [16].

### 3.4 Chemical Bonding and Sealing Ability

The chemical bonding and sealing property of Bioactive restorative materials also provide essential mechanical and interfacial benefits. Materials made with glass ionomer have been extensively known to chemically attach onto enamel and dentin, allowing less of the material to be held mechanically and minimal preparations to be made in the cavity. This aspect is very useful in the pediatric dentistry practice, in which maintaining good tooth structure is a priority, and cooperation can restrict the possibility of complex operative interventions [15].

The adequate closure of toothrestoration interface is essential in the prevention of micro-leakage, marginal staining, post-surgical sensitivity and recurrent caries. Bioactive substances can improve the marginal integrity and reduce bacterial infiltration with the formation of intimate adaptation and ion-mediated interaction with surrounding tissues. Giomers also have advantages in terms of their sealing performance and their high esthetics and polishability in comparison with some other traditional type of ionomer-based materials, and may be applicable to the area of restorative care among children. Several factors like chemical bonding and sealing capability is therefore a contributor not only in facilitating restoration retention but also biological success of caries management.

### 3.5 Pulp Protection and Dentin Repair

The ability to preserve the pulp and cause dentin repair can be mentioned as one of the most clinically relevant therapeutic properties of certain bioactive restorative materials. This is of particular concern to children dentistry, in which deep caries of the primary teeth can be a threat to pulpal health and tooth vitality maintenance is a key treatment outcome. The bioactive materials that contain calcium silicate and other variants may release calcium ions and create an alkaline environment in the process of promoting pulp healing, reducing inflammation, and promoting the formation of reparative dentin or dentin bridge formation [16].

The effectiveness of these materials in preservation processes of pulp depends on their biocompatibility. They also agree with the points of biological caries management and vital pulp therapy in terms of providing tissue healing rather than mere cavity closure. This skill would be applicable within the pediatric environment particularly because it may be able to save the life of primary teeth and prevent more comprehensive procedures. Thus, it is possible to regard pulp protection and dentin repair as a notable treatment advantage of the bioactive restorative materials and justify their increasing relevance in the current pediatric dentistry.

### 3.6 Therapeutic Significance in Pediatric Dentistry

The processes of ion release, remineralization, antibacterial activity, chemical bonding, sealing potential, and the pulp-supportive effects indicate why bioactive restorative materials gain more significance in dental practice in childhood (Table 2). Their clinical potential is not limited to rebuilding lost tooth structure but it facilitates a more general clinical objective of managing disease, maintaining vitality and reducing reintervention [14]. In children, with a high caries activity, low levels of cooperation, and high chances of recurrent lesions, these characteristics render bioactive materials especially useful in an evidence-based and minimally invasive restorative strategy.

**Table 2: Mechanisms of Action of Bioactive Restorative Materials**

| Mechanism | Therapeutic Effect | Clinical Relevance in Pediatric Dentistry | Reference |
|---|---|---|---|
| Ion release (fluoride, calcium, phosphate) | Remineralization, inhibits demineralization | Reduces recurrent caries risk | [16] |
| Remineralization | Mineral repair of enamel and dentin | Supports minimally invasive treatment | [15] |
| Antibacterial activity | Reduces biofilm and acid production | Prevents secondary caries | [14] |
| Chemical bonding & sealing | Reduces microleakage | Improves restoration longevity | [15] |
| Pulp protection & dentin repair | Promotes dentin bridge formation | Useful in deep caries management | [16] |

## 4. Clinical Effectiveness in Pediatric Caries Management

### 4.1 Restoration Survival and Longevity

Survival and longevity of bioactive restorative materials under conditions of functional mouth is the most meaningful parameter of clinical performance of these materials in pediatric dentistry. In children, the success of restorations is not only related to intrinsic properties of the material but also to caries risk, size of the cavity, the occlusal load, tooth type and cooperation of the patient. Bioactive materials, especially glass ionomer-based materials, resin-modified glass ionomers and giomers have attracted attention due to the restorative property as well as therapeutic properties which can enhance long-term performance [8]. Their ability to release fluoride, provide chemical adhesion, and promote remineralization can help to increase the survival of the restorations by mitigating the occurrence of recurrent demineralization along the edges of the restorations [15].

Nonetheless, the longevity of restoration is a material factor. Traditional glass ionomer cements have been highly appreciated due to their cariostatic effect and clinical convenience, but might fail in long-term survival in stress bearing posterior restorations due to less fracture resistance and wear strength [14]. The resin-modified glass ionomers and giomers tend to show a better durability because of their higher physical properties and therefore, are more applicable in the restorations where bioactivity is needed and at the same time, longevity. Therefore, even though bioactive materials have obvious therapeutic benefits, their clinical efficacy in the long term should be viewed regarding the particular clinical needs of the pediatric restorative care [14].

**4.2 Prevention of Secondary Caries**

Among the greatest clinical benefits of bioactive restorative materials, it is possible to mention their ability to prevent secondary caries as one of the leading causes of restoration failure in children. Secondary caries is the condition that commonly occurs at the interface between the teeth and the restoration due to the presence of plaque, microleakage or continuing cariogenic challenge. Bioactive materials have the ability to minimize this risk, achieving it by releasing fluoride, ion exchange, and localized remineralization, which strengthen adjacent tissue and inhibit demineralization [8].

There is a growing body of systematic evidence that bioactive restorative materials can offer some meaningful benefits in the secondary caries control of secondary caries than more passive restorative options. This is especially significant in the pediatric patients who have a tendency of being high caries, lack in good plaque management skills and frequently may need repeated restorative treatment. The materials that have the ability to serve as therapeutic reservoirs can hence not only enhance the success of the prevailing restoration but also the biological stability of the restored tooth in the long-term. Through this aspect, the clinical application of bioactive materials lies not only in restoring the missing structure but actively in the maintenance of caries [11].

**4.3 Marginal Adaptation and Microleakage**

Marginal adaptation is an essential factor of restorative success in pediatric dentistry since inadequate marginal adaptation may lead to microleakage, postoperative hypersensitivity, recurrent caries, and early premature failure of restorations. Such bioactive restorative materials as glass ionomer cements and resin-modified glass ionomers provide a significant benefit as they are chemically bonded to enamel and dentin. Interfacial sealing is enhanced and unnecessary reliance on large-scale mechanical retention is minimized by this property, and it is advantageous in minimal invasive pediatric surgery [15].

Minimized microleakage is particularly beneficial in children, whose caries outcome may develop rapidly in primary teeth and thus have a high probability of undermining restorations when marginal integrity is compromised. Other bioactive resin-based materials such as giomers could also provide desirable marginal adaptation and offer a better esthetic and polishability. This is added to their capability to create a more stable interface with tooth structure which is considered to improve clinical outcomes through restraint of bacterial penetration and conserves the integrity of surrounding tissues. Thus, the performance of bioactive materials in the management of pediatric caries is directly associated with the sealing capacity and the interfacial performance [14].

**4.4 Mechanical Performance and Wear Resistance**

Despite bioactive restorative materials possessing the characteristics of bioactive assets, they are supposed to have adequate mechanical behavior to withstand occlusiveness forces besides functional wear. This is particularly so in the posterior restoration of children; masticatory stress, parafunctions and multi-surface forms of cavity shapes may subject the material durability to the test. Though traditional glass ionomer cements have clinical advantage, biologically active and resistant to compressive and tensile stress, they are generally restricted by lower compressive and tensile strengths as compared to resin-based composites. This would lead them to have a shorter life expectancy in places of high loads [10].

The solution to these has been to develop resin-modified glass ionomers, giomers and more recent bioactive formulations, which possess superior mechanical and wear resistant properties. Such materials must have the capability of withstanding therapeutic ion release and an enhanced fracture resistance, polish retention and durability during operation. However, the trade-off between the bioactivity and the mechanical strength remains a main issue and no single material can be used in all pediatric restoration situations. The material selection thus must be provided according to their possibilities as well as necessities in terms of the mechanical demands of the restoration [11].

**4.5 Moisture Tolerance and Handling in Children**

The ability to handle a material under real-life treatment conditions is highly important in clinical success in pediatric dentistry. Children tend to be challenging to control in regards to moisture due to their lack of cooperation, contamination of salivary, reduced attention span, and practical limitations of operating in small mouths. Moisture-tolerant restorative products come in handy in this respect. Glass ionomer cements and resin-modified glass ionomers are especially beneficial since they are not as technique-sensitive as the traditional resin composites and can be used in moderately good results even the ideal isolation could not be provided [15].

Inconvenience, less chairside time, and less complexity of the procedure are other aspects that increase the clinical utility of bioactive materials in children. These attributes are particularly applicable to the community-based care, less invasive treatment methods, and working with anxious or very young patients. The potential to affect the success of the restorations in pediatric groups may then significantly depend on the

materials that can combine satisfactory durability with clinical convenience [4].

### 4.6 Esthetic and Functional Outcomes

In addition to the biological and mechanical justifications, the restorative materials applied to restore the teeth in children should be capable of providing adequate esthetic and functional outcomes. The restoration is becoming pressurized to be tooth-colored, smooth and aesthetically acceptable by the patient and parents particularly in the anterior and premolar regions. It is in this area that resin-modified glass ionomers, bioactive composite and even giomers are predominantly used because they are more polishable, translucent and color stable, as compared to the conventional glass ionomer cements. It is possible that they can enhance patient and parent satisfaction without its therapeutic effects and their esthetic performance [11].

Clinically, an effective restoration in pediatric patients should preserve tooth restoration, occlusion, mastication, and tooth vitality until such a restoration is naturally exfoliated or retained in young permanent tooth. Bioactive restorative materials also work towards these effects not by merely replacing the structure but by reinforcing the surrounding tissues in teeth and facilitating biological stability. In line with this, esthetic success and functional performance must be considered to be part of the overall clinical performance of bioactive materials in the management of caries in pediatrics [8].

## 5. Comparative Evidence and Critical Appraisal

### 5.1 Comparison with Conventional Restorative Materials

Comparative study between bioactive restorative materials and conventional restorative materials forms the key to the role of these materials in managing caries in children. Traditional materials including composite resin and traditional restorative systems are traditionally strong in mechanical strength, esthetic and clinical familiarity [17]. They however, are mostly passive in their behavior and do not take part in remineralization or biological repair. Bioactive materials, on the contrary, provide therapeutic purposes in the release of fluoride, calcium, and phosphate ions that might be used to control caries and support the tooth structure around. This difference is especially significant in the pediatric dentistry equipped with restorations that are exposed to the higher risks of recurrent caries as well as with the preference of the minimally invasive interventions that are biologically supportive [18].

Clinically, traditional restorative substances can be quite satisfactory in terms of strength and esthetics but their effectiveness is frequently contingent on perfect clinical environments, particularly moisture control and careful technique. These needs in children may not be easily achieved at all times [19]. Under these circumstances, bioactive materials, and more specifically, the glass ionomer-based systems and other related ion-releasing restoratives might have an edge since they offer a reasonable restorative performance with a therapeutic effect and easier clinical manipulation. They can minimize demineralization and, possibly, limit the number of caries recurrences, which makes them an interesting alternative to the high-risk pediatric patients [20].

### 5.2 Comparison Among Different Bioactive Materials

Not every bioactive restorative material behaves similarly and comparison of the restorative materials indicate significant variations in their clinical applicability. Controlled glass ionomer cements have been particularly appreciated in terms of ion release, as well as, remineralization potential. It has been shown that calcium- and phosphate-modified glass ionomer cements can potentially increase bioactivity and mineral exchange in the interface between the tooth and restoration and augment their preventive and therapeutic efficacy [17]. These materials find application especially in pediatric dentistry due to their ability to be chemically adhesive, release fluoride, and their relative ability to resist moisture.

Other bioactive substances include calcium silicate-based systems and giomer-like substances which can offer alternative benefits to a clinical scenario. Materials based on calcium silicate are more closely related to the protection of the pulp, dentin repair and biological healing, whereas giomer-type restoratives are more commonly preferred with their esthetics, recharge of fluoride and appropriate mechanical properties [21]. Thus, it has been implied by the comparison of bioactive materials that the materials are indication-specific. In high-caries-risk cases, materials having strong remineralizing capacity might be the best choice; in case of visible restorations or stress-bearing restorations, materials with superior mechanical and esthetic properties can be used. The described variability demonstrates the importance of selecting materials very carefully instead of thinking that every bioactive system can be used similarly and deliver equal benefits [19].

### 5.3 Strengths of Current Clinical Evidence

There are various strengths of the existing literature on bioactive restorative materials. To begin with, there is a growing awareness that management of caries in children should be done using minimally invasive and biologically-based measures as opposed to using purely mechanical means of restoring cavities [18]. This change has promoted the investigation of restorative substances that can aid in remineralization, seal reliability, along with pulp protection, which renders the literature clinically pertinent to present healthcare practice among children [20].

Second, the recent reviews have begun to view restoration longevity as a multifactorial outcome with the influence of material itself, as well as patient risk, cavity design, oral environment, and factors related to an operator. This wider view enhances the clinical utility of evidence at hand by considering the idea that restorative effectiveness in children as a factor that is multifaceted than just isolated laboratory qualities [19]. Moreover, the increasing popularity of esthetic and

functional rehabilitation in pediatric dentistry has contributed to the assessment of restorative materials both regarding their therapeutic and patient-centered outcomes, which is a strong advantage of the modern clinical research [22].

### 5.4 Limitations of Existing Studies

Although these strengths exist, the existing evidence base has some significant limitations. A heterogeneity in study design, materials tested, evaluation criteria and follow-up periods are one of the greatest concerns. This complicates face-to-face comparison of studies and constrains the power of generalized conclusions. Several studies have only considered short-term results, and the long-term effects and reliability of restorations and secondary prevention of caries need to be tracked over a long time in order to be significant [19].

The other weakness is that some of the evidence available is not produced in the specific population of children but on the basis of other general restorative dental studies. The oral environment, behavioral issues, and anatomy of primary tooth vary basically compared to the adult conditions, such that the findings of general restorative studies cannot be always directly translated to children [17]. Also, there are studies with a focus on laboratory or mechanistic properties but without appropriate correlation with clinical outcomes. Consequently, the alleged benefits of antibacterial, remineralizing, or sealing cannot be specified fully in practice with children despite the promise of claims, the magnitude of which has not been completely defined to date [21].

### 5.5 Gaps in Pediatric-Specific Evidence

The key gap in literature is that there is relative paucity in long-term comparative clinical trials on bioactive restorative materials that have a pediatric-specific characteristic. Despite the growing popularity of the minimally invasive and biologically active approach to caries treatment among modern pediatric methods, there is still a paucity of strong evidence comparing various bioactive substances in primary and young permanent teeth. Further research is required to identify and compare the performance of these materials based on the size of the lesions, type of cavity, caries risk condition, age group, and behavior management issues [20].

Little exists as well in terms of patient-centered and functional outcomes among children such as restoration acceptability, esthetic satisfaction, ease of placement in non-cooperative patients, and cost-effectiveness in routine pediatric care. As pediatric restorative decisions can be complicated by the time of treatment, cooperation of children and long term maintenance imperatives, it can be concluded that additional future research must include these factors in comparison to the traditional indicators of survival and failure. Moreover, there is a lack of evidence on the performance of bioactive restorative materials in such special pediatric conditions as deep caries, selective caries removal, early childhood caries, and children with a high burden of oral diseases [23].

### 5.6 Critical Appraisal

Potential evidence indicates that bioactive restorative substances have significant benefits over traditional substances in pediatric dentistry, especially with regard to remineralization, secondary caries, and support of the tooth body biologically [17]. Nevertheless, such benefits must be seen with a grain of salt since the findings are still not balanced in material types and clinical signs. Bioactive materials are clinically relevant, and the increasing attention to minimally invasive caries treatment contributes to the following fact: the literature lacks sufficiently standardized and long-term pediatric controlled clinical trials to determine the undeniable superiority of one material over another [20].

The current evidence, therefore, justifies the application of bioactive restorative materials as the potential and clinically viable intervention in the treatment of caries among children, though not as effective and universal replacements of all traditional restoratives. They are useful in that they are used in an indicatorative mode, preventive care integration, and in line with current biological treatment ideals [19]. More comparative-methodology studies on pediatrics in the future will be necessary, as they need to find answers to their long-term effectiveness and maximize their application in evidence-based clinical practice.

## 6. Clinical Implications for Pediatric Practice

### 6.1 Indications for Use in Primary and Young Permanent Teeth

Bioactive restorative materials possess high clinical potential in primary and young permanent teeth because of therapeutic characteristics as well as biologically interactive properties [23]. Bioactive materials can be favored in primary teeth, where the rapid development of caries, high volume of pulp chambers, and shorter lifespan imply the need of conservative and effective treatment. Their functionality of releasing fluoride and other ions enables them to control caries as well as increase the longevity of restorations in high-risk children groups. Pulp vitality is very important in young permanent teeth especially where the root formation is not well developed. Bioactive materials may facilitate this goal by facilitating remineralization and sustaining an opportune environment to further maturation of roots [24].

These materials are particularly recommended when the carious lesions are early and moderate, the patients are at high risk of caries and where moisture control is a problem. They can also be used in community-based and least invasive treatment environments, in which they need to be easy to apply and have therapeutic advantages.

### 6.2 Material Selection Based on Caries Risk and Cavity Type

A proper choice of the material is one of the determinants of clinical success in pediatric restorative dentistry. Individualized evaluation of caries risk, cavity size, location and functional requirements should be used to determine the type of bioactive restorative

material to be used [25]. Glass ionomer-based systems are frequently the materials of choice in children with a high caries risk because they have high fluoride release and remineralization potential. These materials have the capability of providing continuous shield against demineralization and secondary caries.

In the case of small, non-stress bearing cavities, there is a possibility of having conventional glass ionomer cements as they are easy to place and cariostatic. Larger or multiple surface restorations, especially in posterior teeth, might, in contrast, need higher mechanical strength materials, which might be resin-modified glass ionomer or bioactive composite. In esthetically sensitive fields, they can use materials with giomers or bioactive composites so that they can strike a balance between esthetic requirements and therapeutic advantages. Hence, the choice of the materials must depend on the biological and functional needs of the given clinical situation.

### 6.3 Role in Minimally Invasive Dentistry

The paradigm of minimally invasive dentistry places the bioactive restorative materials in the focus, as it focuses on structural preservation of the tooth, early intervention and the prevention of the disease as opposed to massive tissue ablation. These materials facilitate what is termed minimally invasive strategies since they enable clinicians to leave the affected dentin which is potentially remineralizable, instead of excising it all. The fact that they are able to chemically bond to tooth structure decreases aggressive cavity preparation, which is a preservation of healthy enamel and dentin. Also, they can be used to prevent the advancement of caries and induce calcification of the remaining demineralized tissue due to its ion releasing property [26]. This renders bioactive materials especially the preferred material in methods like atraumatic restorative therapy and selective caries removal that are frequently used in the field of pediatric dentistry.

### 6.4 Relevance in Deep Caries and Pulp-Preserving Approaches

The treatment of deep caries in children should be done with a lot of care so that pulpal exposure is avoided and so that the tooth becomes vital. There has been significant relevance in the application of bioactive restorative materials especially calcium silicate-based materials and some ion-releasing systems in pulp-preserving methodology [27]. Their capacity to decompose calcium, alkaline generation, and the encouragement of the regeneration of the dentin promotes the restoration of the pulp-dentin complex. These materials are also highly applicable in indirect treatment of pulp, pulpotomy procedures and other treatments that are vital to pulp like the regenerative potential of the material used in the treatment process where biological compatibility is vital. Bioactive materials are useful in enhancing clinical outcomes through facilitation of dentin bridge formation and minimization of the bacterial activity in the management of deep caries. This is in line with current pediatric dentistry finding that emphasize on pulp vitality preservation rather than more invasive treatment [28].

### 6.5 Practical Considerations for Pediatric Dentists

Besides their biological and mechanical qualities, practical considerations are very important in the effective utilization of bioactive restorative materials in children. Particularly in pediatric patients, where cooperation may be limited and the length of the procedure can be intolerable, such factors as easiness of handling, decreased sensitivity of technique, shorter working time and the ability to tolerate prolonged working periods is of great importance. Other factors that can be considered as a cost-effectiveness and availability of materials particularly in community and public health contexts. Clinicians need to determine what benefits newer bioactive materials have, and what tradeoff they must make with their availability and affordability. Moreover, proper preparation and understanding of the material handling procedures are necessary in order to achieve the best results. Lastly, the introduction of bioactive restorative materials in the pediatric practice should be accompanied with extensive caries management protocols, such as preventive care, diet therapy, fluoride therapy, and follow-up. Bioactive materials cannot be considered isolated solutions to a problem, but rather, as part of a larger evidence-based network of pediatric oral health care.

## 7. Conclusion

Bioactive restorative materials have gained considerable progress in the management of dental caries in children, and such materials provide consolidation of functions of restorative and therapeutic means in one clinical procedure. As compared to traditional materials that mostly replace lost tooth structure, bioactive materials actively participate in the remineralization, ion exchange, antibacterial effects and pulp protection, and as such help in the minimally invasive and biologically oriented treatment strategies. These properties are especially useful with children who tend to have a high caries risk, lesion progression, as well as have behavior management and moisture control difficulties. It is shown that bioactive materials may have a positive clinical impact by increasing the lifetime of the restorations, decreasing secondary caries, and improving the marginal integrity, but the effectiveness differs based on the type of material used and the state of clinical conditions. Glass ionomers and giomers have their own benefits and newer bioactive composites also have their own merits, yet none can be said to be universally suitable to all situations in pediatric cases. As a result, the selection of materials should be done in regards to personal characteristics of a patient, the peculiarities of a cavity, and the goals of treatment. As good as the current findings are, the available evidence is limited due to short follow up and varied study designs. Thus, more structured, longitudinal clinical trials on pediatrics are needed to provide conclusive instructions and maximize the incorporation of bioactive restorative substances into the standard practice of pediatrics.

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