

Color Adjustment Potential Of Single Shade Composite Restorative System: A Narrative Review

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The demand for highly esthetic restorative materials has led to continuous advancements in resin composite technology, particularly in the development of single-shade composite systems. These materials are designed to simplify clinical procedures by eliminating the need for complex shade selection while maintaining acceptable esthetic outcomes. Their performance relies on the concept of color adjustment potential (CAP), also known as the chameleon effect, which enables the material to visually blend with surrounding tooth structure. Unlike conventional composites that depend on pigments, single-shade systems utilize structural color mechanisms to achieve shade matching. However, several clinical factors may influence this optical behavior, including restorative technique, cavity depth, and light-curing protocols. The degree of polymerization and light transmission can affect the final color and translucency of the restoration. In addition, thermocycling, which simulates intraoral temperature fluctuations, may lead to material aging and color instability over time. Changes in the resin matrix and filler interface can alter light reflection and absorption properties. Despite the growing use of these materials, there is still limited evidence regarding how these variables interact to influence CAP. Therefore, evaluating the combined effect of restorative techniques, curing modes, and thermocycling is essential to determine the long-term esthetic performance of single-shade composite restorations.

1. Introduction

Modern dentistry prioritizes natural-looking, tooth-colored dental composites due to patient demand for esthetic results, became key driver for innovation. Early composites suffered from limitations in durability and appearance, but modern advancements in resin technology have improved mechanical properties and wear resistance, while filler advancements enhance structural integrity and esthetic mimicry of natural teeth. Bonding agents have also become more effective, improving the longevity and clinical success of these restorations.¹

Indeed, single-shade composite systems are an innovation in esthetic dentistry that simplify shade matching by using optical phenomena like structural color to adapt to surrounding tooth shades, a characteristic known as the "chameleon effect". These systems reduce procedure time and inventory by eliminating the need for multiple shades.² However,

while single-shade composites offer promising visual results and convenience in clinical settings, some studies suggest multi-shade systems provide a more accurate and superior shade match when evaluated instrumentally in a laboratory environment.³

Alongside material advancements, ongoing research into dental curing technologies is vital to improving resin composite restorations by optimizing light-curing units and techniques to achieve adequate polymerization depth and reduce shrinkage stress, ultimately enhancing restoration longevity.⁴ Collectively, these innovations aim to provide clinicians with materials that offer improved esthetics, enhanced durability, and simplified handling, ultimately leading to superior patient care and satisfaction.⁵

2. The Role of Dental Resin Composite Composition in Esthetic and Curing Properties

2.1. Organic Resin Matrix Composition

The organic resin matrix is a fundamental component of dental composites, as it governs curing behavior, handling properties, polymerization kinetics, durability, and long-term esthetic performance. The chemical structure of the monomers, including molecular weight, viscosity, and flexibility, directly influences polymerization shrinkage stress and degree of conversion (DC).^{6,7} The structural backbone of most contemporary dental composites is a blend of high-molecular-weight dimethacrylate monomers. Among these, Bisphenol A Glycidyl Methacrylate (Bis-GMA) and Urethane Dimethacrylate (UDMA) are the most prevalent.⁸

Bis-GMA is favored for its rigid central aromatic core and its ability to form a strong polymer network. However, the presence of two hydroxyl groups leads to strong intermolecular hydrogen bonding and extremely high viscosity. This high viscosity hinders efficient mixing with inorganic fillers and restricts polymer chain motion during polymerization, resulting in a lower final DC and compromising the mechanical properties, reliability, and longevity of the restoration.⁹

UDMA is often used as an alternative or in combination with Bis-GMA. Compared to Bis-GMA, it has lower viscosity and greater flexibility, facilitating a higher degree of conversion and a denser polymer network. UDMA-based composites also exhibit lower water sorption and higher color stability, as the absence of hydroxyl groups reduces hydrophilicity and improves resistance to water degradation. Formulations containing equal or higher amounts of UDMA than Bis-GMA have demonstrated favorable mechanical properties.¹⁰

To counteract the high viscosity of monomers such as Bis-GMA and improve clinical handling, manufacturers add low-viscosity diluent co-monomers, most commonly Triethylene Glycol Dimethacrylate (TEGDMA), which often constitutes a significant portion of the resin matrix. While TEGDMA effectively reduces viscosity and increases polymer chain mobility, facilitating a higher DC, its use compromises the long-term esthetic performance of the composite.¹¹

The primary drawback of TEGDMA is its high hydrophilicity, which significantly increases the material's propensity for water sorption. An increase in the proportion of TEGDMA in a Bis-GMA-based resin has been shown to increase water uptake.¹ This water

sorption is a critical trigger for several degradative processes, including hydrolytic degradation of the polymer matrix, chemical component leaching, and ultimately, color change.¹²

The optimization of mechanical properties creates a fundamental compromise with long-term color stability. Although high DC is essential for mechanical strength and initial color stability, the use of TEGDMA as a diluent in high-strength Bis-GMA systems increases DC while simultaneously reducing matrix hydrophobicity. This directly links initial mechanical optimization to long-term esthetic failure caused by water sorption and hydrolytic processes.¹³

Indeed, water penetration into the resin matrix initiates hydrolysis, chemically degrading the polymeric structure and accelerating component discoloration.¹⁴ This hydrolytic degradation often targets ester linkages within dimethacrylate monomers, causing polymer network breakdown and byproduct leaching, which further compromises the restoration's integrity and esthetics.¹⁵

Esthetically, the refractive index (RI) of the monomer blend is a crucial factor for the initial color and translucency of the composite. The matrix must have a RI that closely matches that of the inorganic fillers to minimize light scattering at the filler-matrix interface, which is essential for achieving a natural, translucent appearance and a good "chameleon effect".¹⁶

The primary monomers each possess distinct refractive indices, which manufacturers must carefully balance. Bis-GMA has a relatively high refractive index (approx. 1.55),¹⁷ which is advantageous as it closely matches the RI of many barium and strontium glass fillers commonly used in composites.¹⁸ This inherent compatibility makes Bis-GMA a foundational monomer for achieving good optical integration. UDMA has a slightly lower refractive index (approx. 1.48-1.51), offering formulation flexibility.¹⁷

It can be blended with Bis-GMA to fine-tune the final RI of the matrix to match specific filler systems. In contrast, the diluent monomer TEGDMA has a significantly lower RI (approx. 1.46).¹⁶ While essential for viscosity control, adding TEGDMA to a Bis-GMA-based matrix will lower the overall RI of the blend.¹⁹ If not properly accounted for with a corresponding filler choice, this can create an RI mismatch, thereby increasing the material's opacity.²⁰

Furthermore, the RI of the resin matrix is not static; it increases as the monomers polymerize into a denser polymer network.²¹ Dental manufacturers must therefore formulate the initial monomer blend to ensure that the RI of the final, cured matrix is the value that precisely matches the RI of the inorganic fillers.¹⁶ This complex formulation is essential for the initial shade match and translucency of the restoration immediately after placement and curing.²² This carefully engineered optical balance is directly threatened by the chemical stability of the matrix over time.²³ The hydrophilicity of TEGDMA is particularly detrimental to long-term esthetics in this regard.²⁴

Water has a very low RI (approx. 1.33). When a composite with a hydrophilic matrix absorbs water from the oral environment, the water molecules infiltrate the polymer network, lowering the overall RI of the matrix. This change disrupts the original RI match between the matrix and the filler particles.¹⁶ The resulting RI mismatch leads to increased light scattering, causing the restoration to gradually lose its translucency, appear more opaque, and ultimately fail esthetically by losing its color integration with the surrounding tooth.²⁵

2.2. Inorganic Filler Systems

Dental resin-based composites (RBCs) are composed of an organic resin matrix reinforced with rigid inorganic filler particles, including quartz, glass, fiberglass, ceramics, and naturally occurring minerals. These fillers significantly enhance the mechanical performance of the material by increasing stiffness, wear resistance, fracture toughness, and elastic modulus. In addition to mechanical reinforcement, the incorporation of fillers improves dimensional stability by reducing polymerization shrinkage, limiting water sorption, and decreasing the coefficient of thermal expansion.²⁶

Recent progress in filler engineering has resulted in the introduction of novel filler systems such as oxide-based fillers, alkaline silicate glass fillers, biomimetic fillers, and organic–inorganic hybrid materials designed to enhance both the clinical performance and functional properties of dental restorative materials.²⁷

The performance of dental resin composites is strongly influenced by the type and composition of inorganic fillers incorporated within the material. Mixed oxide fillers contribute to improved mechanical strength and thermal stability, whereas pre-polymerized fillers are primarily included to enhance handling properties and maintain surface integrity.^{28,29}

The addition of barium glass fillers allows radiographic detection of restorations while also reinforcing the composite structure.³⁰ Silica fillers play a key role in improving wear resistance and regulating light interaction within the material.¹ In contrast, ytterbium trifluoride is mainly used to provide radiopacity without compromising the esthetic appearance of the restoration.³¹

The filler loading, which refers to the relative amount of filler dispersed within the resin matrix, is a critical determinant of the overall performance of resin-based composites. In addition, filler particle morphology significantly affects material properties; spherical particles decrease surface area and interparticle friction, while irregularly shaped fillers promote mechanical interlocking within the matrix. Consequently, RBCs formulated with spherical fillers typically exhibit lower polymerization shrinkage, improved color stability, and reduced stress generation when compared with materials containing irregular filler particles.^{32,33}

RBCs are commonly classified according to filler size and distribution into macro-filled, micro-filled, hybrid, modern hybrid, and nano-filled categories. Macro-filled composites exhibit high mechanical strength but demonstrate inferior surface smoothness and polish retention. In contrast, micro-filled composites provide superior esthetic qualities; however, their reduced filler content makes them more prone to fracture. Hybrid composites were developed to achieve a balance between aesthetic appearance and mechanical performance, while modern hybrid formulations further enhance surface finish and polishability. Nano-filled composites incorporate nanoscale filler technology to minimize polymerization shrinkage without adversely affecting strength and esthetic.²⁶

These materials are based on methacrylate resin systems and specialized curing techniques and are classified as nano-filled or nanohybrid composites.⁸ Nano-filled composites contain uniformly distributed nanoscale fillers, whereas nanohybrids combine nanosized and conventional fillers. The adoption of these advanced filler systems, enhance wear resistance, polishability, and overall performance, improving the predictability and long-term durability of resin-based composites in restorative dentistry.^{34,35}

2.3. Nano-Composites

Modern systems utilize primary nano-sized fillers (often less than 100 nm) or specialized supra-nano spherical fillers. In single-shade systems, these fillers are carefully sized and shaped to generate structural color and maximize surface smoothness and gloss retention, which is critical for the "chameleon effect".¹³

Because the primary nanoscale filler particles are smaller than the wavelength of visible light, they scatter light less, which results in higher translucency and allows the composite to better absorb and reflect the color of the surrounding tooth structure.³⁶ The uniform, nanoscale particles also allow for a very high filler loading, providing excellent mechanical strength while maintaining superior polishability and gloss retention.³⁷ From a curing standpoint, the reduced light scattering by nanoparticles can enhance light transmission through the material, potentially improving the depth of cure compared to composites with larger, more irregular fillers.³⁸

The ability of any composite material to blend effectively, referred to as color adjustment potential (CAP), is highly sensitive to the optical interface between the filler and the matrix.²⁰ Light attenuation within the composite occurs exponentially, primarily through scattering and absorption, particularly at the interfaces between the filler and the organic matrix, especially when there is a RI mismatch.³⁹

To maximize light propagation and translucency (a property vital for CAP and depth of cure), manufacturers strive for a precise RI match between the filler particles and the polymerized resin matrix.⁴⁰ If a significant RI mismatch exists, excessive light scattering occurs, leading to reduced translucency, increased opacification, and potential "shadow-like" effects at the restoration margins.²⁰

2.4. The Silane Coupling Agents

The incorporation of coupling agents into dental resin-based composites is essential for strengthening the interfacial adhesion between filler particles and the polymeric resin matrix, thereby enhancing both the physical and mechanical properties of the material. These agents improve filler wettability, promote uniform particle distribution, and decrease resin viscosity, which contributes to the formation of a stronger and more durable composite structure. In addition, coupling agents enable efficient stress transfer from the resin matrix to the commonly used coupling agents are silane compounds, such as 3-mercaptopropyl-trimethoxysilane (MPS) and amino-silanes.^{27,41}

More profoundly, the hydrolytic stability of this layer is paramount for color retention. Degradation of the silane interface permits water and oral fluids to penetrate the filler-matrix boundary.¹² This compromised interface creates porous pathways that readily trap pigments and biofilms, significantly magnifying the visual impact of extrinsic staining agents and accelerating surface roughening. Therefore, preserving the chemical integrity of the silane interface is foundational to the material's ability to maintain its CAP and overall esthetic durability over time.⁴²

2.5. Additives

The monomers of RBCs formulated in combination with a variety of supplementary components, such as co-monomers, initiators, accelerators, inhibitors, and stabilizing agents, to establish a balanced consistency and polymerization of the resin. According to the method of curing, RBCs are classified as heat-cured, cold-cured, light-cured, or dual-cured RBCs. Among these, light-cured composites are the most used and rely on photo-initiator systems typically incorporated at concentrations ranging from approximately 0.1 to 1 wt %. The optimal amount of initiator is determined by the specific photosensitizer employed and is influenced by factors such as solubility, photochemical efficiency, color characteristics, and biocompatibility. To prevent premature polymerization during storage, inhibitors such as hydroquinone and butylated hydroxytoluene are included to delay the polymerization. Stabilizing agents are incorporated to maintain long-term color stability, while fluorescent additives are used to improve optical properties by absorbing ultraviolet and violet light and emitting light in the blue spectrum, which helps to mask yellow hues. Furthermore, the development of novel co-monomer systems containing aldehyde and diketone functionality have the potential for enhancing the mechanical strength, chemical resistance, and optical performance of resin-based composites, contributing to improved performance and durability.^{32,43}

Opalescence is an optical phenomenon in which a material appears bluish under reflected light and orange–brown under transmitted light, resembling natural enamel, and results from the scattering of short-wavelength light by fine particles.⁴⁴ In composites, opalescence is controlled by managing light scattering caused by differences in the refractive indices between the resin matrix and fillers,⁴⁵ with ceramic fillers additives such as ZrO₂, Al₂O₃, and TiO₂ used to optimize this property.⁴⁶ Opalescence can be optimized by various approaches, including functionalizing silica fillers with organic groups to create inorganic–organic hybrid fillers, increasing the monomer-to-filler ratio, or reducing particle size to approximately 100 nm to achieve the desired optical effect.⁴⁶

Pigments play a critical role in resin-based composites by enabling effective color matching with natural dentition. To ensure long-term esthetic stability, these colorants must remain chemically stable and resistant to alteration within the oral environment. Oxide-based pigments are commonly employed, with ferric oxide providing red tones and ferric hydroxide contributing yellow coloration, selected for their durability and resistance to degradation so that color integrity is preserved throughout the clinical service life of the restoration.⁴⁷ In contrast, in single-shade composite resins, nano filler with a diameter smaller than the wavelength of visible light can produce structural color without the addition of any pigments. Because the production of structural color depends on the size and distribution of fillers.⁴⁸

3. Esthetic Dentistry

3.1. The Growing Demand for Esthetics in Modern Dentistry

In contemporary dental practice, esthetic outcomes are a key determinant of restorative success, with patient satisfaction and the psychological impact of a natural-looking smile serving as essential indicators of clinical effectiveness.^{49,50} Tooth color is often the most noticeable dental feature and is essential for achieving a harmonious smile. Beyond esthetics,

an attractive smile significantly enhances self-esteem and confidence, positively influencing social and professional interactions.^{51,52}

Additionally, investing in dental esthetics promotes self-acceptance, enhances communication and networking, and contributes to a more positive overall outlook on life.⁵³ Modern dentistry emphasizes esthetics in response to rising patient expectations for restorations that blend seamlessly with natural teeth. This demand has driven ongoing advancements in dental materials and techniques, with accurate shade matching being a fundamental skill for achieving natural results and patient satisfaction.^{54,55}

Achieving optimal esthetic results with resin composites is a complex process closely associated with their color properties, such as compatibility, stability, and interaction with surrounding tooth structures. The concept of color in dentistry extends beyond simple shade selection, encompassing dynamic optical phenomena and the material's ability to visually integrate with its environment.^{56,57}

3.2. Fundamentals of Color Perception and Measurement in Dentistry

Understanding color perception is fundamental in esthetic dentistry for producing natural and attractive restorations, as it requires comprehensive knowledge of light behavior, dental tissues, and restorative materials. Color is generated by the spectral composition of visible light (approximately 380–780 nm) reflected or transmitted by an object and interpreted by the human visual system.^{58,59}

The retina contains three classes of cone photoreceptors (peaking roughly in the red, green, and blue regions) whose signals combine to produce trichromatic color vision.⁶⁰ Thus, color is fundamentally a physiological perception of light mediated by the observer's sensory and neural processes. In practical terms, dental color matching is based on a light–object–observer relationship, in which the illumination, the optical properties of the tooth or restoration, and the observer's perception all play essential roles. Variations in the light source, material characteristics, or observer-related factors—such as color vision, visual acuity, or experience—can significantly influence the perceived shade.^{61,62}

Human enamel and dentin have complex optical properties that affect color perception. Natural teeth are translucent and opalescent: short (blue) wavelengths tend to be scattered and reflected, while longer (orange-red) wavelengths transmit through enamel.⁴⁶ As a result, teeth often exhibit a bluish tint on reflection and a warmer tint in transmitted light. Teeth also fluoresce under ultraviolet light (emitting a faint blue light) so they appear whiter and brighter under daylight.⁶³ These phenomena mean that a dental restoration must mimic not only the base color but also translucency, scattering, and fluorescence of natural enamel. In instrumentation and in shade design, such subsurface effects must be considered to achieve a lifelike match.⁶⁴

The focus on shade matching demonstrates that this simplification does not compromise esthetics; instead, it is accomplished through an innovative approach to material optics, reflecting an advanced understanding of light interaction with dental tissues and restorative materials.⁶⁵ Key aspects of dental color include the light–object–observer framework that governs color perception, the three color dimensions—hue, value, and chroma—the influence of different illuminants, and the optical properties of both natural teeth

and restorative materials. Early systems, such as Munsell's color space, categorized colors according to these three dimensions.^{63,66}

By mastering these principles, dentists can better communicate with technicians, select appropriate materials, and ultimately produce restorations that blend seamlessly with the patient's smile.⁶⁷ The three color dimensions challenge dentistry, as traditional visual shade matching is affected by lighting, eye fatigue, and individual perception, often leading to esthetic restoration failures.⁶⁸

To reduce the subjectivity of visual shade matching, objective techniques such as spectrophotometry are essential, providing numerical, quantifiable color data. Using spectrophotometers in dental research enhances scientific rigor by delivering standardized, reproducible measurements that minimize subjective bias.^{69,70} This shift moves from visual shade matching to quantifiable measurements, enhancing reliability in tooth color analysis and improving consistency and accuracy in clinical outcomes.⁷¹

4. Evolution and Classification of Dental Resin Composites: A Focus on Shade Systems

4.1. Conventional Multi-Shade Resin Composites

In esthetic dentistry, the direct composite layering technique, initially developed in the 1980s, continues to be regarded as the benchmark for reproducing the polychromatic characteristics of natural dentition. This approach facilitates optical integration between dental tissues and restorative materials through stratified color application, whereby the final hue of the restoration emerges from the combination of multiple composite layers with distinct chromatic and opacity properties. Nevertheless, achieving precise color congruence is inherently challenging due to variations in layer thickness, structural composition, and the optical behavior of enamel and dentin. Consequently, conventional multi-shade composites, characterized by differences in shade, chroma, and opacity, demand advanced clinical proficiency, a meticulous shade selection process, and result in increased procedural complexity, chairside duration, and treatment costs.²

4.2. Group-Shade Resin Composites

Group-shade resin composites are manufactured in a restricted spectrum of shades, with each variant specifically designated to correspond with a defined range of dental shade guides.⁷²

4.3. Single-Shade Composites

In response to the clinical demands for simplified yet highly esthetic restorative solutions, resin composite materials have undergone continuous modifications.⁷³ This evolution has led to the introduction of "single-shade" composite systems. These innovative materials were specifically developed to streamline the shade selection process and enhance the accuracy of shade matching.⁷⁴

Single-shade composites represent a significant innovation in restorative dentistry, evolving from traditional multi-shade systems to improve efficiency and esthetics by offering improved shade-matching capabilities through a "chameleon effect" that allows the single material to blend with the surrounding tooth structure.² This advancement addresses the time-consuming and subjective challenges of traditional shade selection, offering a simpler

approach to achieving harmonious esthetic outcomes.⁷⁴ Additionally, the development of single-shade composites, utilizing "smart monochromatic technology" to replicate the color of adjacent teeth, represents a strategic move towards simplifying restorative procedures by eliminating the need for multiple shades.⁷⁵

Moreover, the introduction of mono-shade composites marks a fundamental shift in how color is achieved in dental restorations. Unlike conventional multi-shade resin composites, where shade properties are primarily based on intrinsic factors such as incorporated pigments,² mono-shade materials possess a unique ability to blend with a wide range of classical shades, thereby reducing restorative procedure time and simplifying the color selection phase in direct restorations.⁷⁶

After placement, these composites can reflect specific tooth color wavelengths and adapt chromatically to surrounding tooth structures, providing natural shade adjustment.⁷⁷ This distinction highlights that advancements in dental materials are not solely focused on improving mechanical properties but also on enhancing clinical efficiency, reducing chairside time, and minimizing potential for human error in esthetic procedures.⁷⁵

4.4. Optical Properties and Blending Mechanisms of Single-Shade Composites

The chameleon effect is the phenomenon where a single-shade dental composite material appears to match a range of surrounding tooth colors due to its unique optical properties, such as light scattering, diffusion, and translucency.⁷⁸ The underlying mechanism involves sophisticated light scattering and internal diffusion within the material, allowing it to interact with and integrate seamlessly into its surroundings. This dynamic color adaptation goes beyond a simple, static color match.⁴⁹

Translucency is crucial for their color-blending ability, allowing some high translucent dental composite to match surrounding teeth by reflecting and refracting light through a unique «pearl structure», creating structural color rather than relying on pigments. This high translucency enables seamless integration with the natural tooth, providing a chameleon-like effect and eliminating the need for multiple shades.⁴⁹ This property allows the underlying substrate color to significantly influence the final shade of the restoration, resulting in an enhanced blended appearance.⁶⁵

The exceptional translucency and shade-matching ability of some high translucent dental composite are due to Smart Chromatic Technology, which uses uniform, supra-nano spherical fillers and a specific filler fraction to create structural color, an effect where the material interacts with light to produce color.⁷⁵ This precise combination allows the composite's red-to-yellow structural color to mix with ambient light and the tooth's natural color, enabling it to adapt to any shade. The interaction between the resin matrix and fillers is crucial, as a close refractive index match reduces light scattering and enhances the material's ability to blend with the surrounding tooth structure.⁷⁵

Furthermore, the RI of single-shade dental composite material changes during polymerization, allowing it to blend seamlessly with surrounding tooth structures due to the better light interaction within the material; this is a key aspect of its "smart chromatic technology" that enables color matching across various tooth shades.⁷⁹ The scattering coefficient of a resin-based composite is primarily determined by particle size, with larger

particles increasing scattering when their diameter approximates or exceeds the wavelength of incident light, while absorption is linked to the resin matrix and any colorant pigments.⁸⁰

Therefore, any factors influencing light interaction within the material—such as material thickness, the quality of light curing, surface properties, and changes due to aging—will directly impact the effectiveness and longevity of this chameleon effect.⁸¹ Furthermore, the reliance on extrinsic light interaction and the optical properties of the surrounding tooth, rather than intrinsic pigmentation, signifies a fundamental shift in how these materials achieve color integration.⁴⁵ Consequently, the final perceived color of a single-shade restoration is a complex interplay of the material's intrinsic translucency, the underlying tooth shade, and the spectrum of incident light.⁸²

In multilayer resin composite restorations, the final perceived color is not determined by each composite increment independently, but rather by the optical interaction that occurs between adjacent layers. When light enters the restoration, it travels through the superficial composite layer and interacts with the underlying composite before being reflected to the observer. As a result, the overall color outcome depends on the combined optical behavior of the different layers rather than the intrinsic shade of a single layer alone. Furthermore, variations in the thickness and translucency of the composite layers can influence light transmission within the restoration and consequently alter the final color appearance.⁸³

This dynamic interaction implies that the material's "CAP" is not a static property but one that is highly influenced by its environment.⁸⁴ This dynamic characteristic makes the investigation of variables such as restorative techniques, curing modes, and thermocycling particularly pertinent, as these factors can significantly alter these optical interactions and, consequently, the material's esthetic performance over time.⁸⁵

Sanad M et al. ⁸⁶ evaluated the color matching ability of a single-shade resin composite, a single-translucency resin composite, and a multi-shaded resin composite across three tooth shades and two cavity depths. The multi-shaded composite showed superior color matching in all shades, while cavity depth had no significant effect on color matching among the materials.

Cruz da Silva E et al.⁸⁷ evaluated the color correspondence of two single-shade composite resins in extracted human teeth compared to multishade composite resins instrumentally and visually. They concluded that single-shade composite resins showed different color-matching results when compared to multi-shade resins, both in spectrophotometry and visual evaluations.

Zhu J et al.⁸⁸ evaluated the instrumental and visual color adjustment potential (CAP-I) (CAP-V) of a single-shade composite resin compared with conventional multi-shade composite resins against different background colors. They concluded that the CAP was dependent on the material type and background color, single shade composite exhibited the CAP and the most pronounced color shifting ability.

Silva E et al.⁸⁹ assessed the color-matching ability and color recovery of unprepared teeth when using single-shade composites and a universal composite in large restorations by spectrophotometer. They concluded that despite their ability to match the surrounding enamel reasonably, none of the composites evaluated in large restorations fully recovered the color observed in unprepared teeth.

5. Understanding Color Adjustment Potential (CAP) in Dental Restorations

5.1. Definition and Clinical Significance of CAP

The concept of CAP represents a key parameter in the assessment of dental composite esthetics, particularly for contemporary single-shade materials, as it quantifies the ability of a restorative material to achieve seamless visual integration with adjacent tooth structures.⁹⁰ A high CAP is essential for attaining optimal esthetic outcomes in restorative dentistry.⁷⁸

However, the interpretation of CAP values in terms of clinical effectiveness remains unclear. Currently, no universal standard defines a CAP threshold for effective color shifting. Nevertheless, some studies have suggested empirical reference values, with CAP ≈ 0.20 considered indicative of color adjustment and CAP ≈ 0.50 reflecting stronger color-shifting ability (Pereira Sanchez et al., 2019; Altınışık & Özyurt, 2023; Durand et al., 2021).⁹¹

Composites exhibiting elevated CAP demonstrate superior ability to blend with the natural tooth, thereby minimizing perceptible differences between the restoration and adjacent dentition. This property also mitigates the impact of imperfect initial shade selection, enabling clinicians to achieve satisfactory esthetic results even when the chosen shade is not ideal. Furthermore, a high CAP enhances procedural efficiency by reducing the number of shades required, thereby simplifying the shade selection process and streamlining clinical workflow.^{90,92}

A high CAP enhances the esthetic integration of restorations by closely replicating the color, translucency, and luster of natural teeth, resulting in a more harmonious appearance within the dental architecture.⁹³ Materials with elevated CAP also reduce the likelihood of remakes or replacements, conserving chairside time and lowering treatment costs.⁹⁴ Additionally, this property enables the composite to adapt its color dynamically, facilitating simpler shade selection, improving clinical efficiency, and ultimately increasing patient satisfaction.⁹⁰

Conversely, dental composite with a low CAP, also known as low color blending ability, can result in restorations that don't perfectly match the natural tooth, appearing artificial, attracting stains, and ultimately leading to patient dissatisfaction and in many cases, necessitating premature replacement.⁹⁴ The clinical significance of CAP, therefore, extends beyond immediate esthetics to encompass patient satisfaction and the longevity of the restoration.⁹²

5.2. Factors Influencing CAP

The CAP of resin composites is a multifactorial property governed by intrinsic material characteristics, clinical application variables, and post-placement factors such as curing protocols and aging processes, including thermocycling, moisture exposure, and staining. External influences on CAP are closely related to application parameters, as the placement technique whether incremental layering or bulk-fill affects the material's optical interaction with the surrounding tooth structure. In addition, restoration depth plays a critical role in color matching and blending, while the shade of the underlying tooth substrate significantly influences the final perceived color of the restoration. The CAP is an important factor influenced by the optical behavior of resin composites. Incremental layering modifies light

propagation within the material, affecting scattering, reflection, and interaction with adjacent substrates, which ultimately impacts the blending effect and perceived color.⁹⁴

The CAP of resin composite restorations is influenced by a multitude of factors, encompassing both the inherent properties of the material and external application parameters.⁹⁴ Dental composite composition, including key components like filler content and particle size determine light scattering, while the organic resin matrix type influences translucency and light absorption. Factors such as filler-matrix refractive index matching and the presence of opacifiers further modify these properties, allowing for materials like single-shade composites to adapt their color to surrounding tooth structure.²¹

Inherent material characteristics play a critical role in CAP. Filler content, for example, can influence the opacity of composite resins and consequently affect their blending behavior. However, CAP extends beyond simple opacity or translucency, as it is governed by the complex interaction of light scattering, reflection, and transmission, which are modulated by filler concentration, particle size, and intrinsic optical properties such as opalescence.⁹²

The composition of the resin matrix, including the presence of unreacted functional groups, significantly influences the material's stability and its susceptibility to discoloration. Additionally, the photo-initiator system involved in the polymerization process plays an important role in determining the color stability of the restorative material.⁹⁵

Restoration thickness is a critical factor influencing CAP, as increased material thickness generally reduces translucency and CAP. This reduction limits the material's ability to visually integrate with surrounding tooth structures, making accurate color matching more challenging, particularly in deeper cavities.⁷⁸ Curing and aging processes significantly influence the CAP of resin composites. Insufficient polymerization can compromise both physical and optical properties, increasing susceptibility to discoloration. Additionally, repeated temperature changes may adversely affect color stability, while prolonged exposure to oral moisture and staining agents can lead to progressive discoloration over time.⁹⁶

The photoinitiator system is considered an important factor influencing the color adjustment potential (CAP) of resin composites. By affecting intrinsic color, light absorption, and polymerization behavior, photoinitiators alter the optical performance of the material. These changes influence translucency, scattering, and the way light interacts with both the composite and the surrounding tooth structure. Consequently, variations in photoinitiator type and composition can directly impact the degree of color blending and the overall CAP of resin-based restorations.^{43,97,98}

Sari C et al.⁹⁹ evaluated the color matching of universal composite restorations with various cavo-margin designs. They found that CAP-I was significantly higher at 1 month in universal composite groups compared to single shade resin composite groups, regardless of bevel preparation, in all groups, showed significant similar CAP-I results.

De Castro F et al.¹⁰⁰ evaluated the influence of cavity wall thickness 3, 2, or 1 mm on CAP of single-shade composites. They concluded that wall thickness, especially at 1 mm, negatively impacted the color of single-shade composites.

Shin H et al.¹⁰¹ evaluated the influence of cavity depth on the CAP and translucency of a single-shade composite resin compared to multi-shade composite resins. They concluded

that single-shade composites offer superior shade-matching ability. And the decrease in CAP with increasing cavity depth indicates potential limitations in deeper restorations.

Kanchanomai V et al.¹⁰² assessed the impact of different background tooth colors on the visual color adjustment potential (CAP-V) of two single-shade flowable resin composites, evaluating their suitability for anterior restorations. They concluded that the first single shade flowable resin composite material could serve as an alternative material for the injection molding technique in anterior teeth with lighter shades, while that the second single shade flowable resin composite material may be more suitable for darker shades.

Ismail EH and Paravina.⁹⁴ evaluated the CAP of resin composites and the factors influencing it. They found that CAP is affected by material type, cavity design, and the surrounding substrate, all of which play a role in improving color matching and the overall esthetic outcome.

Kowalska et al.¹⁴⁴ evaluated the photoinitiators used in resin-based composites. They reported that photoinitiator systems affect optical properties and color stability, where CQ may cause yellowing, while alternative systems such as TPO and Ivocerin improve color stability and esthetic performance.

6. Method of evaluation of color adjustment potential

A comprehensive evaluation of CAP requires the integration of both objective and subjective assessment methods to ensure clinical relevance.¹⁰³ Accordingly, CAP was assessed using two indices: an instrumental index (CAP-I) and a visual index (CAP-V). The CAP-I was calculated as $1 - (\Delta E\text{-DUAL} / \Delta E\text{-SINGLE})$ based on CIEDE2000 color differences, where $\Delta E\text{-DUAL}$ represents the color difference between the test and base shades in dual specimens, and $\Delta E\text{-SINGLE}$ represents the corresponding difference measured in separate single specimens while the CAP-V was calculated as $1 - (V\text{-DUAL} / V\text{-SINGLE})$ using visual scores obtained from dual and single specimens.¹⁰⁴

6.1. Subjective (Visual) Evaluation

The Munsell color system is extensively utilized for visual color assessment and is founded on a three-dimensional color framework. Value (lightness) is determined initially by selecting a reference tab that most accurately represents the perceived lightness or darkness of the color, with values extending from white (10/) to black (0/). Subsequently, chroma is assessed using tabs of comparable value but progressively increasing saturation, ranging from achromatic gray (/0) to highly saturated colors (/18). Hue is identified in the final stage by matching color tabs that correspond to the previously established value and chroma, and is classified on a numerical scale from 2.5 to 10, in increments of 2.5, across ten distinct color families: R, referred to as red; YR, referred to as yellow-red; Y, referred to as yellow; GY referred to as green-yellow; G, referred to as green; BG, referred to as blue-green; B referred to as blue; PB referred to as purple-blue; P referred to as purple; and RP referred to as red-purple.¹⁰⁵

Despite its widespread application in clinical dentistry, visual shade selection is inherently subjective and demonstrates limited reproducibility. This method is strongly influenced by the observer's physiological and psychological responses to radiant energy stimuli, rendering it susceptible to variability. Discrepancies in shade determination may arise

from several uncontrolled factors, including visual fatigue, emotional state, aging, prior visual adaptation, illumination conditions, object positioning, and metamerism. Consequently, these limitations highlight the need for more objective, standardized, and scientifically reliable approaches to shade matching in restorative dentistry.¹⁰⁵

6.2. Objective (Instrumental) Evaluation

Within this system, color is defined in a three-dimensional space using the coordinates L^* , a^* , and b^* . The L^* parameter represents lightness, with values extending from 0, corresponding to ideal black, to 100, corresponding to ideal white. The a^* and b^* parameters describe chromaticity along the red–green and yellow–blue axes, respectively. Positive a^* values denote a shift toward the red spectrum, whereas negative values indicate a shift toward green. Similarly, positive b^* values correspond to yellow hues, while negative values represent blue hues.¹⁰⁵

Changes in lightness and chromaticity (ΔL^* , Δa^* , Δb^*), such as those resulting from UV light exposure, are initially evaluated, after which the overall color difference (ΔE^*_{ab}) is calculated using the established mathematical relationship. In 2001, the Commission Internationale de l'Éclairage (CIE) introduced an updated color difference formula, ΔE_{00} , to address limitations related to lightness perception. This formula incorporates additional color attributes and assigns greater weighting to L^* , a factor of particular importance in dental applications.¹⁰⁵

Color differences are commonly interpreted using two key limits: The perceptibility threshold represents the minimum color difference detectable by the human eye, whereas the acceptability threshold defines the limit beyond which color differences are considered clinically unacceptable. Earlier investigations in dental color science based on the CIELAB (ΔE^*_{ab}) system reported broader perceptibility and acceptability limits, with perceptibility values often near 1 unit and acceptability extending to around 3.7 units. Following the development of the CIEDE2000 (ΔE_{00}) formula, which correlates more closely with human visual perception, more consistent thresholds were proposed in contemporary research, typically around $\Delta E_{00} \approx 0.8$ for perceptibility and $\Delta E_{00} \approx 1.8$ for acceptability. These thresholds provide a practical framework for evaluating dental materials, facilitating the interpretation of both visual and instrumental color assessments in clinical practice and dental research.^{104,106}

Furthermore, instrumental color analysis offers distinct advantages over visual shade assessment, as it provides objective, quantifiable, and standardized measurements, reduces observer-related errors, enables rapid data acquisition, and enhances communication between clinicians and dental laboratory technicians. Consequently, colorimeters and spectrophotometers have been developed and refined to overcome the inherent limitations associated with visual shade matching in dentistry.¹⁰⁵

6.3. Colorimeters

Filter colorimeters operate using three or four silicon photodiodes equipped with spectral correction filters. These filters function analogously to signal processors, restricting the spectral characteristics of the light that reaches the detector's surface. Compared to scanning instruments such as spectrophotometers and spectroradiometers, filter colorimeters are limited

in their ability to fully replicate the standard observer functions, which reduces their precision in certain color measurements. However, their rapid and reproducible sensing capabilities make them well-suited for quality control applications. An example of this technology is ShadeEye, a colorimeter designed according to the natural color concept.105

6.4. Spectrophotometers and Spectroradiometers

Spectrophotometers and spectroradiometers are instruments designed to provide the most accurate and reproducible color measurements. Spectrophotometers differ from spectroradiometers primarily by employing a stable light source, which enhances measurement consistency. These instruments are generally constructed in two main designs. The traditional scanning spectrophotometer uses a single photodiode detector that records light intensity at discrete wavelength intervals. The incident light is dispersed into narrow wavelength bands using a monochromator, allowing sequential measurement across the spectrum.105

A more recent design employs a diode array, with individual elements assigned to each wavelength, enabling simultaneous integration across all wavelengths. Both designs provide substantially higher accuracy than colorimeters, as they utilize the full spectral reflectance data for color analysis. In contrast, colorimeters measure only tristimulus values, capturing filtered red, green, and blue (RGB) components of the visible spectrum.105

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