Sains Malaysiana 55(4)(2026): 706-716
http://doi.org/10.17576/jsm-2026-5504-10

Resin-Based Composites: Optical Behaviour, Colour Stability and the Chameleon Effect - A Comprehensive Narrative Review

(Komposit Berasaskan Resin: Tingkah Laku Optik, Kestabilan Warna dan Kesan Chameleon - Satu Kajian Naratif Komprehensif)

SOFYA ZULKIFFLI*, NURUL LIYANA AMINUDDIN & NOOR AZLIN YAHYA

Department of Restorative Dentistry, Faculty of Dentistry, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

Received: 13 January 2026/Accepted: 17 April 2026

ABSTRACT

Aesthetic restorative dentistry demands materials capable of reproducing the complex optical behaviour of natural teeth. Resin-based composites (RBCs) have undergone significant evolution to meet these expectations, particularly in relation to colour stability, optical properties and the chameleon effect. This narrative review synthesises the conceptual foundations and recent evidence regarding optical phenomena in RBCs, including translucency, refractive index matching, fluorescence, opalescence, and metamerism. Special consideration is given to the chameleon effect and colour adjustment potential (CAP), both of which contribute to successful visual integration between restorations and natural tooth structure. The emergence of universal-shade and structural-colour composites such as those employing spherical nano-fillers to generate colour through optical resonance, marks a significant innovation in restorative dentistry. Although these materials simplify shade selection and improve workflow efficiency, their performance remains substrate-dependent and may not reliably match high-chroma or complex aesthetic cases. This review integrates current findings, highlights material-driven optical mechanisms and proposes directions for future research to optimise aesthetic outcomes in restorative practice.

Keywords: Chameleon effect; colour adjustment potential; colour stability; optical properties; resin-based composites

ABSTRAK

Pergigian restoratif estetik menuntut bahan yang mampu meniru tingkah laku optik kompleks gigi semula jadi. Komposit berasaskan resin (RBC) telah mengalami evolusi yang ketara bagi memenuhi keperluan ini, khususnya dari segi kestabilan warna, sifat optik dan kesan chameleon. Ulasan naratif ini mensintesis asas konseptual dan bukti terkini berkaitan fenomena optik dalam RBC, termasuk translusensi, pemadanan indeks biasan, fluoresens, opalesens dan metamerisme. Perhatian khusus diberikan kepada kesan chameleon dan potensi pelarasan warna (CAP), yang kedua-duanya menyumbang kepada integrasi visual yang berjaya antara restorasi dan struktur gigi semula jadi. Kemunculan komposit satu-warna dan komposit warna struktur, seperti bahan yang menggunakan nano-pengisi sfera untuk menghasilkan warna melalui fenomena resonans optik, merupakan satu inovasi penting dalam pergigian restoratif. Walaupun bahan-bahan ini memudahkan pemilihan warna dan meningkatkan kecekapan aliran kerja klinikal, prestasinya masih bergantung kepada substrat dan mungkin tidak dapat memberikan padanan warna yang tekal dalam kes berwarna kromatik tinggi atau kes estetik yang kompleks. Ulasan ini mengintegrasikan keputusan semasa, menekankan mekanisme optik yang dipacu oleh sifat bahan serta mencadangkan hala tuju penyelidikan masa hadapan bagi mengoptimumkan hasil estetik dalam amalan restoratif.

Kata kunci: Kesan kameleon; kestabilan warna; komposit berasaskan resin; potensi pelarasan warna; sifat optik

INTRODUCTION

The evolution of aesthetic restorative dentistry has been closely intertwined with advancements in resin-based composite (RBC) technologies. Since their introduction in the 1960s, composites have progressively replaced amalgam in many clinical contexts due to their ability to bond to tooth structure, conserve healthy tissue and mimic natural dental aesthetics. Yet even with decades of refinement, achieving an imperceptible restoration remains a clinical and scientific challenge. The visual integration of a restoration into its surrounding environment depends on the accurate reproduction of natural optical behaviours such as translucency, fluorescence, opalescence, scattering and surface gloss, all of which vary significantly between enamel and dentin (Schmeling et al. 2013; Volpato, Pereira & Silva 2018).

Shade matching in clinical dentistry is strongly affected by the limitations of human visual perception. Multiple factors including operator experience, ambient lighting, eye fatigue, metamerism, and the intrinsic variability of tooth colour complicate the process (Boksman 2007). Traditional multi-shade composite systems were designed to address these challenges by imitating the double-layer optical effect of enamel and dentin. However, the increasing demand for simplified clinical workflows and reduced material inventory stimulated the development of universal-shade composites. These materials claim to adapt to a broad spectrum of tooth shades through enhanced translucency, engineered optical scattering or structural-colour mechanisms that eliminate the need for conventional pigments (AlHamdan et al. 2021; Humbel et al. 2022). These developments highlight the growing need to understand not only material composition, but also the underlying optical principles that govern aesthetic performance. Underlying these innovations is the recognition that natural teeth exhibit complex optical interactions. Enamel's semi-translucent structure allows light penetration and scattering, whereas dentin with its higher chromatic intensity provides the dominant hue and value of the tooth (Nahsan et al. 2012). Reproducing these properties requires sophisticated manipulation of filler type, filler load and refractive index relationships within composite materials (Lee 2007; Ota et al. 2011). The resin matrix and photoinitiator systems also contribute to optical behaviour, affecting not only translucency but also the long-term stability of colour under intraoral conditions (Malekipour et al. 2012).

Colour stability represents another major determinant of long-term aesthetic success. Resin composites are susceptible to both intrinsic and extrinsic discolouration processes. Intrinsic changes arise from resin matrix degradation, water sorption, oxidation and breakdown of the filler–matrix interface (Abu-Bakr et al. 2000; Paravina et al. 2006). Extrinsic discolouration occurs through absorption or adsorption of pigments from beverages such as coffee, tea, and red wine (Ertaş et al. 2006; Topcu et al. 2009). The degree of colour stability varies depending on the composite formulations, reflecting differences in filler content, resin matrix formulation and surface properties. Nano-filled and nanohybrid composites demonstrate superior resistance to staining compared with microfilled and macrofilled composites (Beltrami et al. 2018). This improved performance is largely related to smaller and more uniformly distributed filler particles, which allow these materials to achieve smoother surfaces after finishing and polishing, thereby reducing extrinsic staining over time (Beltrami et al. 2018). Beyond shade matching and colour stability, another critical determinant of aesthetic success is the material's ability to visually integrate with surrounding tooth structure.

One of the most intriguing optical phenomena relevant to composite aesthetics is the chameleon effect, which refers to the ability of a restorative material to visually blend with adjacent tooth structure. This effect is influenced by cavity size, the translucency of the material, background shade and the refractive index compatibility of its components (Paravina et al. 2008). When the refractive indices of the resin matrix and filler components are closely aligned, resin composites are able to transmit and diffuse light more efficiently. This optical interaction facilitates visual blending with the surrounding enamel and dentine, enhancing the material's ability to mask underlying tooth colour. Such properties are particularly advantageous in universal or single-shade composite systems that rely on the chameleon effect to achieve satisfactory aesthetic integration (Ota et al. 2012). More recently, the concept of Colour Adjustment Potential (CAP) has been introduced as a quantifiable measure of a material's blending ability, assessed visually or instrumentally (Çubukcu, Gündoğdu & Gül 2023; Pereira Sanchez et al. 2019). CAP has become an important benchmark for evaluating modern universal-shade composites.

The introduction of structural-colour composites, such as those incorporating monodisperse spherical nano-fillers approximately 260 nm in diameter, represents a new frontier in aesthetic restorative materials. Instead of relying on pigments, these materials generate colour through optical resonance phenomena governed by the size and arrangement of their fillers (Furusawa et al. 2023). While they offer simplified shade selection and improved blending in many clinical situations, their performance remains substrate-dependent and may be less effective in deep cavities, high-chroma teeth or restorations requiring precise hue control (De Abreu et al. 2020; Kim et al. 2007).

Despite the growing interest in universal-shade and structural-colour composites, inconsistencies remain regarding their reported optical behaviour, colour stability, and reliability across different clinical scenarios. This lack of consensus underscores the need for a critical synthesis that integrates material-driven optical mechanisms with clinically relevant limitations, rather than focusing solely on simplified shade-matching claims.

Given the rapid expansion of universal composite technologies and the ongoing clinical challenges associated with achieving seamless aesthetic outcomes, a comprehensive synthesis of the optical behaviour, colour stability, and blending mechanisms of resin composites is warranted. This narrative review consolidates current evidence on the optical fundamentals of natural teeth, material chemistry-driven optical behaviour, mechanisms of colour stability and the scientific principles underlying the chameleon effect. By integrating traditional and emerging composite technologies, this review provides a balanced perspective on their clinical implications and limitations.

MATERIALS AND METHODS

This narrative review synthesises current evidence on the optical behaviour, colour stability and optical blending performance, specifically the chameleon effect and colour adjustment potential (CAP), of resin-based composites (RBCs), including universal-shade and structural-colour systems. A narrative approach was adopted to allow conceptual integration of material science, optical principles and clinically relevant outcomes that cannot be adequately addressed through quantitative synthesis alone. A focused literature search was conducted in PubMed, Scopus and Web of Science. Search terms included combinations of 'resin-based composite', 'optical properties', 'translucency', 'colour stability', 'chameleon effect', 'colour adjustment potential', 'universal shade', 'structural colour', 'nano-filled composite', and 'translucency parameter'. The search included all years up to January 2025 and was limited to English-language publications.

Eligible articles included peer-reviewed *in vitro* studies, clinical studies, systematic reviews, narrative reviews, and relevant materials science papers that addressed composite optical behaviour or aesthetic performance. This broad inclusion strategy was employed to capture both experimental and clinically oriented evidence relevant to composite aesthetics. Studies unrelated to dental composites, conference abstracts without full data and non-English publications were excluded. Data extracted from selected studies focused on key material- and optics-related parameters, including resin matrix composition, filler characteristics, refractive index behaviour, translucency and opacity metrics, fluorescence, opalescence, colour stability outcomes and measures of shade adaptation such as Colour Adjustment Potential (CAP) and Translucency Parameter (TP).

In this review, 'shade matching' refers to the conventional process of selecting a composite shade that corresponds to the tooth using visual or instrumental methods. In contrast, the 'chameleon effect' describes the inherent optical ability of a material to blend with surrounding tooth structure without precise shade selection. These concepts are therefore considered distinct and are addressed separately in this review.

RESULTS AND DISCUSSION

A total of 182 articles were identified through database searching. After removal of duplicates and screening based on titles and abstracts, 96 studies were assessed for eligibility. Of these, 52 articles met the inclusion criteria and were included in this narrative synthesis, while excluded studies were omitted due to irrelevance to composite optical behaviour, lack of full data or non-English publication. The findings from the selected literature are synthesised thematically to highlight key optical principles, material-related factors and clinical implications governing the aesthetic performance of resin-based composites.

OPTICAL BEHAVIOUR OF NATURAL TEETH

An understanding of the optical behaviour of resin-based composites must first be grounded in the optical characteristics of natural teeth, which serve as the biological reference for aesthetic restorative materials. The optical appearance of natural teeth arises from the complex interaction between enamel and dentin, each contributing distinct structural and optical characteristics. Enamel, which is composed of highly mineralised hydroxyapatite prisms, is semi-translucent and allows significant light transmission that permits underlying dentin to influence the final perceived colour (Xiong, Chao & Zhu 2008). Although enamel contributes little to chroma, it plays a critical role in modulating brightness, translucency and surface gloss through the way it filters and scatters incident light (Villarroel et al. 2011). These effects are essential in creating the characteristic vitality and depth observed in natural teeth.

Dentin, by contrast, is more organic and contains an extensive network of collagen fibres and dentinal tubules that scatter and absorb light more strongly, making it the primary determinant of tooth hue and chromatic saturation (Nahsan et al. 2012). The visual perception of tooth colour is therefore predominantly driven by dentin, with enamel acting as a translucent overlay that modifies its appearance. This interaction, often described as the double-layer optical effect, explains why successful aesthetic restorations must replicate not only dentin's chromatic properties but also enamel's ability to modulate transmitted and reflected light (O'Brien 1985). Age-related changes such as secondary dentin deposition or enamel thinning may alter this dentin–enamel balance and influence the aesthetic outcome of restorative materials.

In addition to colour and translucency, natural teeth exhibit several other optical phenomena that influence clinical aesthetic outcomes. Dentin displays fluorescence - emitting visible light when exposed to ultraviolet wavelengths - which enhances brightness and contributes to a more natural appearance in varying lighting conditions (Cruz et al. 2023; Schmeling et al. 2013). Enamel also demonstrates opalescence, appearing bluish under reflected light and amber when transmitting light because of selective wavelength scattering governed by its microstructure (Volpato, Pereira & Silva 2018). These intrinsic optical properties are further complicated by metamerism, where tooth colour appears different under varying light sources due to differences in spectral reflectance between enamel, dentin and restorative materials (Kim et al. 2007). Understanding these principles is clinically essential, as the dominance of enamel or dentin optical effects varies with preparation depth, remaining tooth structure and individual anatomy, all of which influence how composite materials should be selected and applied to mimic natural aesthetics. These inherent optical properties of enamel and dentin establish the benchmark against which the optical performance of restorative composites should be evaluated.

OPTICAL PROPERTIES OF RESIN-BASED COMPOSITES

Accordingly, the optical behaviour of resin-based composites is determined by how effectively their material composition and microstructure reproduce these natural light–tissue interactions. The optical behaviour of resin-based composites (RBCs) is determined by interactions among the resin matrix, filler particles, pigments, and photoinitiator systems, each influencing how light is transmitted, refracted, scattered, absorbed and reflected (Lee 2008; Ota et al. 2011). These interactions collectively shape key aesthetic properties such as translucency, opacity, fluorescence, and blending ability. Given the multifactorial nature of these optical interactions, key findings from selected studies are summarised to provide a clearer overview of how material composition influences optical performance (Table 1).

A primary determinant of optical performance is the refractive index (RI) compatibility between the resin matrix and fillers. When their RI values closely match, light scattering is reduced, promoting higher translucency and improved blending with surrounding tooth structure. Conversely, mismatched RI values increase opacity, which may aid in masking but compromise natural translucency. Filler size and morphology further affect light behaviour, as nano-filled and nanohybrid composites permit smoother light transmission and improved gloss retention, whereas larger fillers in microhybrids typically increase opacity and reduce enamel-like translucency (Gürgan, Vural & Miletić 2021; Lee 2007).

Pigments and opacifiers influence hue, chroma, and value. Traditional multi-shade composites rely on metal oxide pigments and titanium dioxide to emulate dentin and enamel, though these additives may heighten metamerism under varied lighting (Kim et al. 2007; Pitel 2013). Universal-shade composites, in contrast, frequently minimise pigment content and instead utilise translucency or structural-colour mechanisms to enhance blending across multiple shades (Humbel et al. 2022). Recent evidence demonstrates that nano-filled systems can produce favourable chameleon behaviour due to refined filler morphology and enhanced scattering control (Chiong, Ting & Zulkiffli 2025).

Fluorescence and opalescence also contribute to lifelike optical behaviour. Fluorescent dyes incorporated into composites help mimic dentin's natural UV-induced emission, although fluorescence intensity varies significantly among commercial systems (Cruz et al. 2023; Schmeling et al. 2013). Opalescence - seen as bluish tones in reflected light and amber tones in transmitted light - is more faithfully reproduced in some nano-filled composites than in highly translucent universal systems (Volpato, Pereira & Silva 2018).

The resin matrix and photoinitiator system further influence both initial appearance and long-term optical stability. Monomers such as Bis-GMA, UDMA, and TEGDMA impact viscosity, polymerisation kinetics and clarity, while residual monomers may oxidise over time and contribute to intrinsic colour change (Malekipour et al. 2012). Camphorquinone imparts a natural yellow tint, whereas newer photoinitiators aim to minimise this while improving depth of cure (Radz 2013).

Quantitative measures such as the Translucency Parameter (TP) and Colour Adjustment Potential (CAP) offer insight into a material's blending behaviour. TP represents the extent of light transmission through a material and is determined by measuring colour differences against white and black backgrounds, providing an indication of translucency that is essential for aesthetic integration, as higher translucency facilitates light transmission and scattering from adjacent tooth structures (Ilie & Hickel 2011). In contrast, CAP quantifies a material's ability to adapt its apparent colour to different background shades and is calculated by comparing the colour difference of the composite on various backgrounds with that of the backgrounds themselves, making it a valuable metric for assessing the blending behaviour of chameleon or universal shade resin composites. Universal-shade composites often exhibit higher TP and stronger CAP values (Çubukcu, Gündoğdu & Gül 2023; Ismail & Paravina 2021; Pereira Sanchez et al. 2019), though excessive translucency may limit masking ability when discoloured substrates are present. While these optical characteristics influence immediate aesthetic integration, their clinical relevance is ultimately governed by how well they are maintained over time under intraoral conditions.

TABLE 1. Summary of optical properties of resin-based composites

Key references	Composite type	Optical parameter	Key finding
Lee (2008)	Microhybrid	Light transmission	Increased filler reduces translucency
Ota et al. (2011)	RBC	Refractive index	RI matching improves blending
Gürgan, Vural & Miletić (2021)	Nanofilled	Surface gloss	Improved optical performance
Humbel et al. (2022)	Universal-shade	Structural colour	Enhanced blending via reduced pigments
Ismail & Paravina (2021)	Universal-shade	CAP/TP	High translucency improves blending but reduces masking

COLOUR STABILITY OF RESIN COMPOSITES

Colour stability is fundamental to the long-term aesthetic success of resin-based composite (RBC) restorations. Despite improvements in monomer chemistry, filler technology, and surface finishing, composites remain susceptible to intrinsic and extrinsic factors that alter their colour over time. These mechanisms are multifactorial and involve both intrinsic material characteristics and extrinsic environmental influences that collectively affect long-term colour stability. Intrinsic discolouration arises from within the composite and is largely influenced by resin matrix composition, degree of conversion and filler–matrix interfacial stability. Hydrophilic monomers such as TEGDMA allow greater water sorption, resulting in polymer swelling, plasticisation and microvoid formation that facilitate pigment infiltration (Malekipour et al. 2012). Residual unreacted monomers and amine-containing photoinitiators may oxidise, producing yellowing over time (Paravina et al. 2006; Radz 2013). Camphorquinone contributes an initial yellow tone that persists if polymerisation is incomplete. The degradation of silane at the filler–matrix interface - especially under acidic or thermal stress - exposes fillers, increases surface roughness and disrupts light scattering, accelerating intrinsic colour change (Beltrami et al. 2018).

Extrinsic discolouration results from the adsorption or absorption of pigments from external sources. Coffee, tea, red wine, cola, and chromogenic foods contain tannins and polyphenols that readily bind to composite surfaces (Ertaş et al. 2006; Topcu et al. 2009). Smoother, well-polished nano-filled and nanohybrid composites exhibit better stain resistance due to reduced pigment entrapment (Gürgan, Vural & Miletić 2021). This is supported by recent *in-vitro* findings demonstrating that nano-filled materials maintain acceptable colour stability even after immersion in staining media, though some ΔE change remains inevitable (Chiong, Ting & Zulkiffli 2025). Lifestyle factors, such as smoking or frequent consumption of coloured beverages, further contribute to extrinsic staining.

Chemical challenges such as acidic drinks, pH fluctuations, alcohol-containing rinses and peroxide-based whitening agents can soften the resin matrix, reduce surface hardness and increase pigment uptake (Alhabdan et al. 2022; Malekipour et al. 2012). A recent evaluation of a single-shade composite also reported significant colour change following coffee immersion despite satisfactory mechanical strength, underscoring the vulnerability of universal materials to staining challenges (Lim et al. 2025). These effects are particularly important for universal-shade and structural-colour composites, which rely heavily on translucency; even minor surface alterations can significantly affect shade perception. The key intrinsic and extrinsic factors influencing colour stability are summarised in Table 2.

TABLE 2. Intrinsic and extrinsic factors affecting colour stability of resin-based composites

Factor category	Specific factor	Mechanism	Effect on colour stability	Key references
Intrinsic	Polymer matrix composition	Hydrophilic monomers increase water sorption	Greater susceptibility to intrinsic discolouration	Malekipour et al. (2012); Paravina et al. (2006)
Intrinsic	Photoinitiator chemistry	Residual monomers oxidise over time; CQ yellowing	Immediate and delayed yellowing	Radz (2013); Abu-Bakr et al. (2000)
Intrinsic	Filler–matrix interface	Silane hydrolysis increases roughness	More plaque retention & staining	Beltrami et al. 2018
Intrinsic	Filler loading	Higher filler reduces resin exposure	Improved colour retention	Gürgan, Vural & Miletić 2021
Extrinsic	Coffee, tea, red wine	Chromogens bind & diffuse into resin	Progressive external staining	Ertaş et al. 2006; Topcu et al. 2009
Extrinsic	Pigmented foods	Acidic pH increases adsorption	Surface staining	Malekipour et al. 2012
Extrinsic	Nicotine	Tar and pigments adhere strongly	Brown surface staining	Topcu et al. 2009
Extrinsic	Surface roughness	Microgrooves trap pigments	Higher stain retention	Yap, Sau & Lye 1998; Beltrami et al. 2018
Extrinsic	Chemical challenges	Matrix softening, decreased hardness	Greater pigment uptake	Malekipour et al. 2012
Extrinsic	Bleaching agents	Oxidative changes alter surface	Reduced colour stability	Alhabdan et al. 2022

As shown in Table 2, both intrinsic factors such as resin matrix composition and filler characteristics, and extrinsic factors including dietary habits and environmental exposure, play a critical role in determining the long-term colour stability of resin-based composites. Clinically, understanding these influences is essential for optimising long-term aesthetic outcomes. Patients with high consumption of staining beverages may benefit from composites with proven stain resistance or from periodic repolishing. For anterior restorations, materials with superior resistance to both intrinsic and extrinsic discolouration should be prioritised, whereas minor shade changes may be acceptable in posterior areas. Despite ongoing improvements in composite formulations, achieving complete colour stability remains challenging, highlighting the importance of material selection, maintenance and patient education. Beyond maintaining colour over time, modern aesthetic composites are also expected to visually harmonise with surrounding tooth structure, giving rise to the concept of optical blending.

CHAMELEON EFFECT AND COLOUR ADJUSTMENT POTENTIAL

The ability of resin-based composites to visually blend with surrounding tooth structure, commonly referred to as the chameleon effect, is a key aesthetic advantage in modern restorative dentistry. This phenomenon occurs when the optical characteristics of a composite allow it to assimilate the chromatic and value properties of adjacent enamel and dentin, thereby reducing the need for precise shade matching. The effectiveness of this blending behaviour is strongly influenced by material translucency, light-scattering behaviour, and the interaction of restorative thickness with surrounding tooth structure. Composites with higher translucency permit greater transmission of environmental colour information, enabling the underlying dentin and peripheral enamel to contribute significantly to the final perceived shade (Vattanaseangsiri et al. 2022). This effect is most pronounced in small or conservative preparations, where a large proportion of natural tooth structure remains to guide light interactions.

Material properties such as refractive index matching, filler morphology and structural optical design also play important roles in achieving effective shade blending. Nano-filled systems, with their uniform and smaller particle distributions, allow smoother light transmission and minimise surface scattering, thereby enhancing the composite's ability to harmonise with natural dentition (Gürgan, Vural & Miletić 2021). Structural-colour composites, which generate chromatic appearance through controlled wavelength scattering rather than pigmentation, represent an advanced approach to shade adaptation. These materials rely on spherical nano-fillers to produce colour through optical resonance, allowing a single shade to adjust across a broad spectrum of tooth colours (Humbel et al. 2022). However, the success of this mechanism is substrate-dependent and typically optimised for mid-value A-range shades, with reduced performance in highly chromatic or low-value dentition (Furusawa et al. 2023). The growing emphasis on optical blending has directly influenced the development of composite systems designed to maximise colour adjustment with simplified shade selection.

To quantify this blending behaviour, the colour adjustment potential (CAP) has emerged as a valuable metric in both research and clinical evaluation. CAP measures the degree to which a restorative material's colour shifts when placed adjacent to or over a different shade, providing insight into its capacity to adapt visually. Both instrumental (CAP-I) and visual (CAP-V) assessments have shown that materials with higher translucency and controlled scattering behaviour exhibit stronger adjustment potential, particularly when used in shallow preparations or thin increments (Çubukcu, Gündoğdu & Gül 2023; Pereira Sanchez et al. 2019). CAP is closely associated with the translucency parameter, reinforcing the concept that blending ability is strongly influenced by how effectively light is transmitted through the composite rather than reflected directly from its surface.

Despite these advancements, the chameleon effect has important clinical limitations. When restorations involve large Class IV defects, deep cavities, discoloured substrates, or teeth outside the A-shade family, the influence of surrounding tissues diminishes, and intrinsic composite properties dominate shade expression. Excessive translucency may produce a greyish or low-value appearance, particularly against darker backgrounds, whereas insufficient translucency reduces blending capacity altogether. Universal-shade composites may therefore underperform in high-aesthetic anterior zones where enamel–dentin layering, incisal opalescence and precise chroma control are essential (De Abreu et al. 2020; Zhu et al. 2023). For such cases, conventional multi-shade systems remain the preferred approach.

Overall, the chameleon effect and CAP offer meaningful advantages in simplifying restorative workflows, reducing shade selection errors, and producing satisfactory outcomes in minimally invasive dentistry. However, their effectiveness is case dependent and clinicians must recognise when universal or highly translucent composites are appropriate and when more structured layering strategies are required. Appreciating the optical mechanisms underlying blending behaviour enables more accurate material selection and ultimately supports more predictable aesthetic outcomes across diverse clinical scenarios. To further illustrate the factors influencing optical blending, key studies evaluating the chameleon effect and colour adjustment potential (CAP) are summarised in Table 3.

UNIVERSAL-SHADE AND STRUCTURAL-COLOUR COMPOSITES

The development of universal-shade composites represents a major shift in restorative dentistry, offering the possibility of reproducing a wide range of tooth shades using a single material. These systems aim to simplify shade selection,

TABLE 3. Summary of studies on chameleon effect and colour adjustment potential

Study	Material	Method	Key finding
Paravina et al. (2008)	RBC	Visual	Smaller cavity size enhances blending
Pereira Sanchez et al. (2019)	Universal-shade	CAP (instrumental)	High translucency increases CAP
Çubukcu, Gündoğdu & Gül (2023)	Single-shade	Visual & instrumental	CAP influenced by thickness
Vattanaseangsiri et al. (2022)	RBC	Experimental	Translucency directly affects chameleon effect
Kobayashi et al. (2021)	Single-shade	Instrumental	Substrate-dependent colour adaptation

streamline inventory requirements and reduce operator variability, particularly in routine clinical procedures. Their aesthetic performance relies heavily on optical mechanisms such as increased translucency, refractive index harmonisation and engineered light-scattering behaviour. When translucent composites interact with surrounding tooth structure, they allow underlying and adjacent tissue to influence the final perceived colour, enabling visually seamless results in small or moderately sized restorations (AlHamdan et al. 2021). This blending effect is particularly advantageous in minimally invasive preparations, where natural tooth structure remains intact to guide light transmission.

Emerging structural-colour composites extend this concept by generating colour through controlled interactions between visible light and uniformly sized spherical nano-fillers. Rather than relying on pigments, these materials produce shade through optical resonance, a phenomenon analogous to structural colours observed in nature. The resulting system can theoretically adapt to a wide range of tooth shades, reducing or eliminating the need for multiple pigments (Humbel et al. 2022). Although this technology offers significant potential, especially for restorations within the A-shade family, its performance remains dependent on enamel thickness, substrate value and cavity depth. Structural-colour composites tend to struggle with high-chroma or low-value dentition, where reliance on translucency alone is insufficient to reproduce natural colour characteristics (Furusawa et al. 2023).

Despite their aesthetic advantages, universal and structural-colour systems also have inherent limitations. Because many of these materials rely on heightened translucency, their masking capability is reduced, making them less suitable for discoloured substrates, deep cavities or cases requiring significant opacity control. In such situations, universal composites may appear greyish or low in value and additional opaquer layers or dentin-shade modifiers may be necessary. The absence of dedicated enamel and dentin shades further restricts their ability to replicate opalescence, incisal halo effects, and other nuanced optical features needed for high-aesthetic anterior restorations. Consequently, while universal-shade composites simplify everyday clinical procedures, they should not be considered replacements for multi-shade systems in cases requiring precise aesthetic replication. Despite these innovations, questions remain regarding whether universal and structural-colour systems can consistently replace conventional multi-shade composites across diverse clinical scenarios.

CONVENTIONAL VS. UNIVERSAL-SHADE COMPOSITES

The growing availability of universal-shade composites has prompted considerable interest in their potential to replace conventional multi-shade systems in routine restorative practice. However, despite their convenience and technological sophistication, significant differences remain in their aesthetic capabilities, optical predictability and clinical performance. Understanding these differences is essential for appropriate material selection, particularly in restorations requiring high aesthetic demand.

Conventional multi-shade composite systems were developed to replicate the optical behaviour of natural teeth through a layering approach, in which dentin and enamel shades are applied separately to mimic the double-layer optical effect. Dentin shades typically possess higher opacity and chroma to simulate the underlying dentin structure, while enamel shades are more translucent, reproducing natural enamel's modulating effect on transmitted and reflected light (Villarroel et al. 2011). This dual-layer method allows clinicians to control hue, chroma, and translucency in a nuanced manner, producing restorations that replicate natural teeth with exceptional precision, even in complex anterior situations. The wide range of available shades and opacities in these systems enables accurate matching of teeth across all value, chroma and hue variations, including B, C, and D families (Da Costa et al. 2010; Østervemb et al. 2011).

In contrast, universal-shade composites aim to replicate many of these optical effects using a single material. Their blending ability stems from increased translucency, refractive index matching and advanced scattering mechanisms, or in some cases, structural-colour technology that eliminates the need for pigments (Furusawa et al. 2023; Humbel et al. 2022). These properties enable universal composites to visually adapt to a range of tooth shades, particularly within the commonly encountered A-shade spectrum. They offer considerable advantages in clinical efficiency, reducing chair-time and simplifying shade selection, especially in minimally invasive procedures where surrounding tooth structure dominates the optical environment (Bakti et al. 2018). In such small-to-medium restorations, universal-shade composites often achieve aesthetic outcomes comparable to conventional multi-shade materials.

However, there are inherent limitations in universal systems that restrict their suitability for more complex restorative scenarios. Since many universal composites rely heavily on translucency to achieve blending, they may produce a greyish or low-value appearance in deep cavities or when placed over dark or stained dentin. The lack of layered control over opacity also challenges their ability to mimic enamel opalescence, incisal halo effects and the nuanced characterisation required in anterior restorations. Studies consistently show that universal-shade composites perform best when cavity size is small and the substrate closely resembles medium-value shades, but their blending capability diminishes in high-chroma or low-value teeth (De Abreu et al. 2020; Zhu et al. 2023). Structural-colour composites, while technologically advanced, also struggle with shade families beyond A-range hues, as their optical resonance properties are optimised for a limited spectrum (Furusawa et al. 2023).

Masking ability represents another key distinction. Conventional multi-shade systems offer dedicated opaque dentin shades designed to conceal discoloured substrates, metal posts and darker dentin. Universal-shade composites, by design, lack such strong masking capability due to their higher translucency, often necessitating additional opaquer or blocking layers. This added step undermines the very simplicity that universal composites aim to provide (Paravina et al. 2006). Furthermore, complex anterior cases frequently require layered characterisation to reproduce natural surface texture, translucency gradients and internal effects such as mamelons features that are unattainable with a single-shade universal material.

Despite these limitations, universal-shade composites remain valuable in many clinical settings, offering an appealing balance between simplicity and aesthetic adequacy. They are particularly effective in routine posterior restorations, paediatric dentistry, small Class III and V cavities, and scenarios where ultra-high aesthetic demands are not prioritised. Meanwhile, conventional multi-shade composite systems continue to serve as the gold standard for high-aesthetic anterior cases, complex layering procedures and situations requiring precise hue, chroma, and translucency control. The choice between universal and multi-shade systems should therefore be guided by clinical context, aesthetic requirements, substrate characteristics and operator preference. These differences underscore the importance of translating material-specific optical behaviour into case-appropriate clinical decision-making. The key differences in optical behaviour, aesthetic performance and clinical applicability between universal-shade and conventional multi-shade composites are summarised in Table 4.

CLINICAL IMPLICATIONS

The clinical application of universal-shade and structural-colour resin composites requires careful consideration of their optical behaviour in relation to case-specific variables. Although these materials provide meaningful advantages by simplifying shade selection and improving workflow efficiency, their aesthetic performance is strongly dependent on cavity size, remaining enamel and underlying substrate characteristics. In minimally invasive preparations particularly small Class III and Class V restorations, universal-shade composites demonstrate reliable blending due to the optical dominance of surrounding enamel and the favourable influence of thin composite increments on colour assimilation (Bakti et al. 2018; Paravina et al. 2006). Their reduced shade inventory and simplified handling also offer practical benefits in general practice, paediatric settings, environments requiring rapid and streamlined procedures.

However, clinicians must exercise caution when using universal-shade materials in cases requiring higher aesthetic precision. In deeper or more extensive restorations, the thickness of composite reduces the contribution of surrounding tooth structure, diminishing the chameleon effect and increasing reliance on the composite's intrinsic optical properties (Zhu et al. 2023). This limitation is particularly evident in Class IV restorations, fractured incisal edges, or cases involving significant enamel loss, where layered enamel–dentin reproduction remains essential for achieving natural translucency, value and chromatic depth. Universal composites also exhibit reduced performance in teeth with high chroma or low value such as C and D shade families because structural-colour mechanisms and high-translucency formulations are optimised primarily for mid-value A-range dentition (De Abreu et al. 2020; Furusawa et al. 2023).

Managing discoloured substrates remains challenging because the high translucency of universal composites limits their ability to mask underlying dark dentin, enamel staining, or metal posts (Ismail & Paravina 2021). In these scenarios, the use of an opaquer or blocking layer becomes necessary, although this additional step diminishes the procedural simplicity that universal-shade systems were designed to provide. Moreover, because these materials rely on light transmission and scattering mechanisms, their appearance is more susceptible to metamerism and variations under different lighting conditions. Accurate shade selection and verification under natural daylight or calibrated lighting remain crucial to ensuring colour consistency (Kim et al. 2007; Schmeling et al. 2013).

TABLE 4. Comparison of optical and clinical characteristics between universal-shade and conventional multi-shade resin-based composites

Parameter	Universal-shade / Structural-colour composites	Conventional multi-shade systems	Clinical implications	Key references
Shade selection	Single-shade; streamlined workflow	Requires matching enamel & dentin shades	Reduces chairside time & operator error	Bakti et al. (2018); Paravina et al. (2006)
Blending capacity	Strong chameleon effect in small cavities	Limited blending; depends on correct layering	Ideal for Class III/V and small defects	Sánchez et al. (2019); Çubukcu, Gündoğdu & Gül (2023)
Translucency	High translucency improves blending	Layered translucency mimics natural optics	Universal shades poor at masking discoloured substrates	Ismail & Paravina (2021)
Masking ability	Weak masking due to high translucency	Good masking with opaque dentin shades	Needed for dark dentin or metal posts	De Abreu et al. (2020); Furusawa et al. (2023)
Performance in large restorations	Less effective in deep or wide cavities	Excellent for Class IV & anterior aesthetics	Multi-shade preferred for complex defects	Zhu et al. (2023)
Special effects	Limited opalescence/halo replication	Enamel modifiers allow detailed characterisation	Needed for high-aesthetic anterior cases	Villarroel et al. (2011)
Polishability	Often excellent due to nano-fillers	Varies by filler size	Useful in paediatrics and routine care	Furusawa et al. (2023)
Workflow efficiency	High efficiency; minimises inventory	More steps and syringes required	Ideal for high-volume practices	AlHamdan et al. (2021)
Ideal clinical scenarios	Small enamel-bounded lesions; primary teeth	Large anterior defects; discoloured teeth	Case selection crucial to avoid mismatch	De Abreu et al. (2020); Furusawa et al. (2023)

Collectively, these considerations demonstrate that universal-shade and structural-colour composites serve as valuable adjuncts rather than replacements for conventional multi-shade systems. While they provide efficient and clinically acceptable results in selected cases, they do not replicate the full optical sophistication required for high-aesthetic anterior restorations. Optimal clinical outcomes depend on a nuanced understanding of material optics, substrate conditions, and patient-specific aesthetic expectations. A case-based, evidence-driven approach enables clinicians to leverage the strengths of both universal and traditional composite systems, ensuring long-term aesthetic stability and natural appearance across a range of restorative scenarios.

CONCLUSIONS

This narrative review highlights that the aesthetic performance of resin-based composites is governed by a complex interplay between material composition and optical behaviour. While advancements in nano-filler technology, refractive index matching and structural-colour mechanisms have improved translucency and blending ability, colour stability remains influenced by both intrinsic material properties and extrinsic environmental factors. The chameleon effect and colour adjustment potential offer meaningful advantages in simplifying clinical workflows, particularly in minimally invasive restorations. However, their effectiveness is highly dependent on cavity size, substrate characteristics and restoration depth. Universal-shade composites demonstrate satisfactory performance in small to moderate restorations but remain limited in high-aesthetic and complex cases where conventional multi-shade layering systems provide superior optical control. Future research should focus on optimising the balance between translucency and masking ability while enhancing long-term colour stability across diverse clinical conditions.

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*Corresponding author; email: dr.sofyazul@um.edu.my