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DIGITAL TECHNOLOGIES FOR TOOTH SHADE DETERMINATION IN MODERN ESTHETIC DENTISTRY: CAPABILITIES, ACCURACY, AND PROSPECTS FOR APPLICATION

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ABSTRACT

Accurate determination of natural tooth color is a key prerequisite for predictable esthetic outcomes in direct and indirect restorations. Conventional visual assessment with standardized shade guides remains widely used, but it is subjective and sensitive to illumination, operator color perception, surface condition, and tooth hydration. The digitalization of dentistry has introduced spectrophotometers, colorimeters, digital photography, intraoral scanners, and dedicated color-analysis software, and recent attention has shifted toward automated image processing and artificial intelligence. This review examines contemporary digital methods of tooth shade determination, their operating principles, reported accuracy and reproducibility, and the factors that influence measurement outcomes. Literature indexed in PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar was analyzed, with priority given to systematic reviews, meta-analyses, and clinical studies published within the past five years. The evidence indicates that spectrophotometry remains the most defensible instrumental reference method, that the clinical accuracy of digital photography depends primarily on standardization of capture and color calibration rather than on camera resolution, and that intraoral scanners achieve high repeatability but variable trueness. Artificial intelligence offers the greatest automation potential, although its evidence base remains constrained by heterogeneous algorithms and limited external validation.

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Keywords: *tooth color, esthetic dentistry, digital dentistry, shade matching, spectrophotometry, digital photography, intraoral scanner, CIELAB, CIEDE2000, artificial intelligence.*

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Introduction

Patients' esthetic expectations of dental treatment have risen considerably in recent years. When teeth are restored with composite materials, ceramic veneers, crowns, or other esthetic constructions, the clinical result is determined not only by the form and functional characteristics of the restoration but also by the degree of its optical correspondence to the natural dental tissues. Even when a restoration is fabricated with high precision, a visible color mismatch may adversely affect the patient's perception of the final result.

The color of a natural tooth is a complex optical characteristic arising from the interaction of light with enamel and dentin. The tooth is not a chromatically homogeneous object: the cervical, middle, and incisal thirds may differ in lightness, chroma, hue, and degree of translucency. Determining a single nominal shade value for the entire tooth surface therefore does not always convey its true optical characteristics.

The most common clinical approach to shade determination remains visual comparison of the natural tooth with tabs from standardized shade guides. This approach is associated with a number of limitations. The result may be influenced by the spectral characteristics of the light source, the color of surrounding objects, the duration of observation, the clinician's visual status, operator experience, fatigue of the visual analyzer, moisture on the tooth surface, and other factors (Chen et al., 2012; Tabatabaian et al., 2021).

The digitalization of dentistry has created the conditions for a transition from subjective shade selection to quantitative color assessment. Spectrophotometers and colorimeters, digital cameras, smartphones, intraoral scanners, and dedicated software are used for this purpose. Contemporary systems make it possible not only to relate tooth color to a specific position on a standard shade guide, but also to obtain quantitative color coordinates, store this information, and transmit it to the dental laboratory (Chen et al., 2012; Ebeid et al., 2022; Hina et al., 2024; Rashid et al., 2023).

Software-based analysis of digital images is of particular interest. With appropriate photographic standardization, a digital image can be used to determine the color coordinates of individual tooth regions, evaluate chromatic heterogeneity, and subsequently compare the resulting data with reference values (Hina et al., 2024; Rashid et al., 2023). The development of machine learning and artificial intelligence further opens the possibility of automating tooth image segmentation, correcting capture conditions, and classifying shade (Shetty et al., 2024).

Aim of the review. The aim of this review was to analyze contemporary digital technologies of tooth shade determination in esthetic dentistry; to evaluate their capabilities, accuracy, reproducibility, and limitations; and to identify promising directions for the development of software-based methods of color analysis.

Materials and Methods

An analysis of the national and international scientific literature devoted to visual and digital methods for determining the color of natural teeth was carried out. The search for publications was conducted primarily in the electronic databases PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar.

The following keywords and their combinations were used: *tooth color, tooth shade, shade matching, digital shade matching, digital dentistry, dental photography, spectrophotometer, colorimeter, intraoral scanner, CIELAB, CIEDE2000, artificial intelligence, machine learning*, and *dental shade selection*.

Priority was given to publications from the past five years and to systematic reviews, meta-analyses, and clinical studies addressing the accuracy and reproducibility of digital methods. Earlier publications were considered when addressing the fundamental principles of dental colorimetry and the threshold values of color difference.

Fundamental Principles of Tooth Color Assessment

Objective digital color assessment requires color information to be expressed in a standardized coordinate system. The CIE L*a*b* color space is widely used in dental research: the L* coordinate characterizes the lightness of the object, a* reflects the position of the color on the red–green axis, and b* its position on the yellow–blue axis (Hina et al., 2024; Rashid et al., 2023).

CIELAB allows color to be expressed not only qualitatively but also quantitatively, which is the fundamental advantage of instrumental and software-based methods. The difference between two measured colors can be expressed by the ΔE metric.

Alongside the classical ΔE*ab, contemporary dental research increasingly employs the CIEDE2000 formula (ΔE00), which accounts for the unequal sensitivity of human vision to changes in lightness, chroma, and hue. The use of ΔE00 permits a more appropriate comparison of an instrumentally recorded difference with its visual perceptibility (Paravina et al., 2015).

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When interpreting the resulting data, a distinction must be drawn between the perceptibility threshold, which is the color difference a person is able to detect, and the acceptability threshold, which is a difference that may be noticeable yet remains clinically tolerable. In a prospective multicenter psychophysical study, the 50:50% perceptibility and acceptability thresholds for dentistry were ΔEab = 1.2 and ΔEab = 2.7, corresponding to ΔE00 = 0.8 and ΔE00 = 1.8, respectively (Paravina et al., 2015). Current data nevertheless indicate that no universal absolute threshold exists for all clinical situations: the threshold may depend on the lightness and chroma of the object under examination and on the characteristics of the observer. Tejada-Casado et al. (2024) demonstrated that the 50:50% acceptability threshold varied from ΔE00 = 2.84 for low-chroma sample pairs to ΔE00 = 2.31 and ΔE00 = 1.80 for medium- and high-chroma pairs, respectively, with observers proving more tolerant of differences in more achromatic samples.

Visual Shade Determination and Its Limitations

The visual method is based on direct comparison of the natural tooth with tabs from standardized shade guides, of which VITA Classical and VITA 3D-Master are the most widespread.

The advantages of the method are its simplicity, its availability, and the absence of any requirement for expensive equipment. At the same time, visual assessment remains subjective. Even a single operator may select different shades for the same tooth when illumination or observation conditions change, and inter-operator variability may be greater still (Chen et al., 2012; Tabatabaian et al., 2021).

The color temperature of the light source, the intensity of illumination, bright items of clothing or make-up worn by the patient, and the color of the walls and surrounding objects are all capable of altering visual perception. Enamel dehydration is a further important factor: with prolonged drying the tooth becomes visually lighter and more opaque, and shade selection is therefore recommended before lengthy dental procedures.

In addition, the natural tooth exhibits pronounced spatial heterogeneity of color. Studies in which color is determined separately in the cervical, middle, and incisal thirds demonstrate differences between individual regions of the same tooth (Rashid et al., 2023; Tabatabaian et al., 2021). Consequently, determining a single shade for the entire crown may result in the loss of esthetically significant information.

Digital Technologies for Shade Determination

Spectrophotometry

The spectrophotometric method is based on recording the quantity of light reflected by the object under examination across different regions of the visible spectrum. The resulting spectral information is converted into color coordinates and, depending on the software of the device, may be related to the shades of standard dental guides.

Clinical dental spectrophotometers are characterized by high measurement reproducibility and by markedly lower dependence on the subjective perception of the operator than the visual method. For this reason, spectrophotometry is widely used in research as the reference method when evaluating new approaches to shade determination (Chen et al., 2012; Ebeid et al., 2022; Vitai et al., 2025).

Spectrophotometric measurement cannot, however, be regarded as entirely independent of the conditions of recording. The result may be affected by the position of the measuring tip, the curvature of the tooth surface, the translucency of the tissues, ambient illumination, and the condition and hydration of the enamel. In addition, the cost of specialized equipment restricts its universal use.

Colorimetry

Colorimeters determine color by measuring light intensity within several spectral bands using appropriate filters. Compared with spectrophotometers, they are of simpler construction and generate color coordinates directly.

Colorimetric devices make it possible to objectify the recording of shade, but their diagnostic capabilities depend on the characteristics of the sensor, the measurement geometry, and the signal

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conversion algorithms. In contemporary dentistry, dedicated spectrophotometers have found wider application in research on the accuracy of color determination.

Digital Photography and Software-Based Image Analysis

Digital photography is one of the most promising means of recording information about tooth color, owing to its accessibility, the possibility of documenting the entire tooth surface, and the potential for subsequent software analysis.

Unlike the point measurement obtained with a spectrophotometer, a photograph contains spatial information about the distribution of color. This makes it possible to analyze the cervical, middle, and incisal regions separately, to evaluate gradients of lightness and chroma, and to convey to the dental technician additional information about the morphology, texture, and optical features of the tooth.

The RGB values recorded by a digital camera are not, however, absolute characteristics of the color of an object. They depend on the camera sensor, the lens, exposure, white balance, the light source, the file format, and internal image-processing algorithms.

The most important condition for using photography for quantitative analysis is therefore standardization. This may include a fixed distance and camera position, constant exposure parameters, the use of a macro lens and flash, color or gray reference targets, control of white balance, and the exclusion of automatic software processing.

A comparative clinical study by Hina et al. (2024) showed agreement between standardized digital photography and spectrophotometric color determination in the majority of observations: agreement ($\Delta E \leq 2$) was found in 42 of 50 cases (84.0%), and the L*, a*, and b* values did not differ significantly between the two methods. The findings of different studies are nevertheless heterogeneous, which points to the substantial influence of the specific protocol of image capture and processing. Lazar et al. (2019), for example, reported that color differences between spectrophotometric measurements and polarized photography lay at or below the 50:50% acceptability threshold in only 23% of cases. Rondón et al. (2022) compared standardized photographic shade analysis with visual shade matching in a panel of 50 observers assessing a light and a dark maxillary central incisor, evaluating both approaches with two different color difference formulas.

This circumstance is of fundamental importance: digital photography is not in itself a method of objective color measurement. Objectivity is achieved only when standardized image acquisition, color calibration, and a validated processing algorithm are combined. Rashid et al. (2023) observed that manual white balance calibration was preferred by the majority of investigators precisely because it significantly improves digital color accuracy compared with automatic correction.

Software analysis may include selection of the tooth region of interest, exclusion of specular highlights, conversion of the original RGB values into a device-independent color space, derivation of the L*, a*, and b* coordinates, and calculation of the color difference relative to a reference.

Such an approach potentially allows a transition from subjective shade selection on a photograph to quantitative evaluation of individual tooth regions.

Intraoral Scanners

Contemporary intraoral scanners are used predominantly to acquire the digital geometry of the dental arches, but a number of models simultaneously record texture and color information. This creates the possibility of determining shade directly during digital scanning, without a separate clinical stage.

The principal advantage of this approach is the integration of color determination into the digital CAD/CAM protocol. The data obtained can be stored together with the digital impression and transmitted to the dental laboratory.

Systematic reviews demonstrate reasonably high repeatability of shade determination by intraoral scanners, but indicators of trueness differ substantially between devices and between studies (Akl et al., 2023; Vitai et al., 2025).

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The meta-analysis by Vitai et al. (2025) showed that intraoral scanners are characterized by high reproducibility, with pooled repeatability between 0.81 and 0.85, but that pooled trueness ranged only from 0.28 to 0.38 relative to spectrophotometry. High repeatability of a result should not therefore be interpreted automatically as high accuracy in determining the true color.

Clinical data reported by Baqleh and Alhouri (2026) likewise showed that the Medit i700 scanner determined the value (lightness) parameter with clinically acceptable agreement, but that its accuracy in full shade determination was insufficient for use as a stand-alone method. Agreement was also higher for molars and canines than for incisors, which is consistent with the greater translucency and more complex optical behavior of maxillary incisors.

At the present stage, therefore, the shade-determination function of an intraoral scanner is more appropriately regarded as a supplementary source of information, particularly where esthetic demands are high.

Factors Affecting the Accuracy of Digital Shade Determination

The digital nature of a method does not preclude the occurrence of error. On the contrary, the final result is formed by a sequence of stages, from the interaction of light with the tooth surface to the software interpretation of the data obtained. The most significant factors include the following:

- the spectral characteristics and intensity of illumination;
- the presence of direct or diffuse light;
- reflections and specular highlights on the enamel surface;
- the degree of tooth hydration;
- the distance and angle of recording;
- the characteristics of the camera or scanner sensor;
- exposure and white balance;
- the presence or absence of polarization;
- internal image-processing algorithms;
- color calibration;
- the choice of tooth surface region for analysis.

Specular highlights are of particular importance. Specularly reflected light may lead to the recording of regions with artificially high lightness that do not reflect the true optical characteristics of the tissues. Cross-polarized photography reduces surface reflections and yields a more informative image of the internal color characteristics of the tooth (Lazar et al., 2019).

Accordingly, a reproducible software-based method of color determination requires not only an analytical algorithm but also a standardized protocol for acquiring the source data.

Artificial Intelligence in Tooth Shade Determination

The development of artificial intelligence and computer vision is forming a new direction within digital dental colorimetry. Machine learning algorithms are potentially able to perform automatic recognition of the tooth in a photograph, segmentation of individual regions, exclusion of highlights and background objects, correction of color distortion, and classification of shade.

The systematic review by Shetty et al. (2024) demonstrated the promise of applying artificial intelligence to dental shade-matching tasks, although the authors noted the need for further standardization of methods, larger training samples, and external validation of algorithms.

A fundamental advantage of the artificial intelligence approach is the capacity to analyze a large number of image features simultaneously. Unlike an algorithm based solely on the mean RGB or L*a*b* values of a defined region, a machine learning model can take into account the spatial distribution of color, brightness, texture, and other characteristics.

Algorithms capable of operating with images obtained by different devices and under varying illumination represent a particularly promising direction. This is important for the possible use of

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smartphones and standard digital cameras outside a strictly controlled photographic studio. Tao et al. (2026) developed such a framework, which incorporates specular highlight suppression and brightness-first perceptual reasoning and requires neither polarizing filters nor device calibration; it achieved 79.12% top-1 accuracy on routine intraoral photographs captured with a range of smartphones and cameras, and 76.0% top-1 accuracy in an independent 50-case observer study.

High algorithm accuracy on its own training sample does not, however, guarantee comparable effectiveness when a different camera, a different light source, or a different patient population is used. Multicenter studies and external verification on independent data are therefore necessary for the clinical implementation of artificial intelligence systems.

Comparative Characteristics of Digital Methods

Spectrophotometry possesses high objectivity and reproducibility and currently remains the best-substantiated instrumental reference approach. Its drawbacks are the cost of the equipment and the predominantly localized nature of the measurement.

Digital photography provides a large volume of spatial information and is convenient for communication with the dental laboratory. Its potential advantages are accessibility and the possibility of software processing. The principal limitation remains the pronounced dependence of the result on standardization of capture and on color calibration. The meta-analysis by Hardan et al. (2022) is instructive in this respect: among the shade selection methods analyzed, only the use of digital photographs produced a statistically significant reduction in color difference relative to conventional shade tabs ($p < .0001$), whereas spectrophotometry showed no advantage over visual guides in the pooled clinical data ($p = .57$).

Intraoral scanning provides convenient integration with CAD/CAM and permits color data to be obtained simultaneously with the digital geometry. The accuracy of shade matching nevertheless depends on the device model, the software, and clinical conditions, and high repeatability is not always accompanied by adequate trueness.

Artificial intelligence systems possess the greatest potential for automation, but the evidence base remains limited by the heterogeneity of the algorithms and datasets employed.

The difficulty of drawing a single conclusion about the superiority of any one method is illustrated by the meta-analysis of Borse and Chaware (2020), which pooled 21 studies of visual shade methods, instrumental shade methods, and the factors affecting shade selection, and reported statistically significant heterogeneity across the included data ($Q = 1038.15$, $df = 20$, $p < .0001$).

Table 1 summarizes the operating principles, reported performance, and principal limitations of the visual and digital methods discussed above. Considered together, these data indicate that none of the existing methods can be regarded as a universal solution for all clinical situations. The choice of technology should be determined by the nature of the restoration, the esthetic requirements, the equipment available, and the accuracy required.

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Table 1

Comparative Characteristics of Visual and Digital Methods of Tooth Shade Determination

Method	Operating principle	Reported performance	Principal limitations
Visual shade guides	Direct comparison of the tooth with tabs of a standardized guide (VITA Classical, VITA 3D-Master)	Lowest agreement with instrumental references; kappa agreement with spectrophotometry as low as 0.2 in one clinical comparison; visual and instrumental thresholds differ significantly	Subjectivity; dependence on illumination, observer experience and fatigue, surround, and tooth hydration
Spectrophotometry	Recording of spectral reflectance across the visible spectrum, converted into color coordinates	Serves as the reference standard in most comparative studies; highest reported precision and accuracy among instrumental methods	Cost of equipment; localized (point) measurement; edge-loss effect; sensitivity to probe positioning, surface curvature, and translucency
Colorimetry	Filtered measurement of light intensity within several spectral bands, generating color coordinates directly	Objectifies shade recording, but has been validated less frequently than spectrophotometry in recent accuracy research	Dependence on sensor characteristics, measurement geometry, and signal conversion algorithms
Digital photography with software analysis	Image-based extraction of RGB values, converted to device-independent CIE L*a*b* after color calibration	Agreement with spectrophotometry ($\Delta E \leq 2$) in 84.0% of cases under a standardized protocol; only 23% of cases within the acceptability threshold when cross-polarization was used without full calibration; significant reduction in ΔE versus conventional tabs in pooled analysis ($p < .0001$)	RGB values are not absolute; strong dependence on sensor, lens, exposure, white balance, light source, file format, and internal processing
Intraoral scanning	Color capture concurrent with acquisition of three-dimensional surface geometry	Pooled repeatability 0.81–0.85 but pooled trueness only 0.28–0.38 relative to spectrophotometry; acceptable agreement for value (lightness) but insufficient for full shade selection	Marked device-to-device variability; high repeatability does not imply trueness; lower agreement for translucent anterior teeth
Artificial intelligence–based image analysis	Learned mapping from image features (spatial color distribution, brightness, texture) to shade classes	79.12% top-1 accuracy across smartphones and cameras without calibration; 76.0% top-1 accuracy in an independent 50-case observer study	Heterogeneous algorithms and datasets; small training samples; limited external validation across devices, illuminants, and populations

Note. ΔE = color difference in the CIELAB color space; RGB = red, green, blue. Reported performance values are drawn from Baqleh and Alhouri (2026), Chen et al. (2012), Hardan et al. (2022), Hina et al. (2024), Lazar et al. (2019), Rashid et al. (2023), Shetty et al. (2024), Tao et al. (2026), and Vitai et al. (2025). Trueness and repeatability figures for intraoral scanning are pooled proportions.

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Discussion

Analysis of the contemporary literature reveals a consistent trend toward objectifying the process of tooth shade determination. The transition from visual shade selection to digital measurement makes it possible to describe color quantitatively and increases the reproducibility of results.

At the same time, the term digital is not synonymous with the term accurate. The results of a digital system are determined by the characteristics of the recording device, the conditions under which the data are obtained, and the algorithm by which those data are interpreted.

The heterogeneity of findings in studies of digital photography is particularly instructive. Under strict standardization, some authors obtain a high degree of correspondence with spectrophotometric data (Hina et al., 2024), whereas other studies demonstrate clinically significant discrepancies (Lazar et al., 2019). Such variability indicates that the further development of the method should be directed not so much toward the use of higher-resolution cameras as toward standardization of the entire chain of color recording and processing. This conclusion is supported by the systematic review of Rashid et al. (2023), which found that under controlled conditions non-proximity digital instruments produced clinical outcomes comparable to those of contact devices, while also reporting that a substantial proportion of the included studies failed to describe the camera apparatus adequately or to control for variation in ambient light.

A similar situation is observed with intraoral scanners. Contemporary devices demonstrate high measurement repeatability, but meta-analytic data do not permit them to be considered a full replacement for the spectrophotometer under all clinical conditions (Akl et al., 2023; Baqleh & Alhouri, 2026; Vitai et al., 2025).

The most promising approach appears to be a combined one, in which digital recording is supplemented by software analysis and the results are compared with objective color coordinates. In such a system the clinician receives not only the designation of a shade from a standard guide but also quantitative information about lightness, color coordinates, and the spatial heterogeneity of tooth color.

Future Perspectives

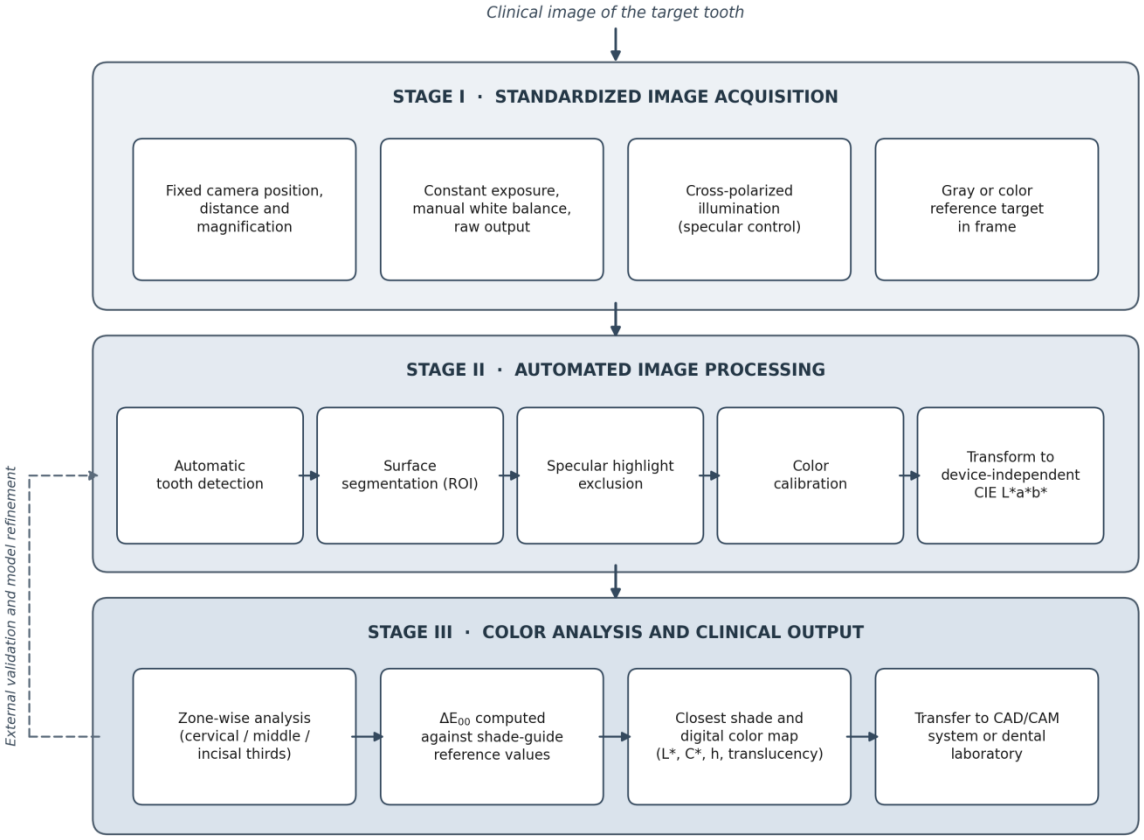
The further development of digital methods of color determination is likely to be associated with the integration of several technologies into a single clinical workflow.

A prospective software system may comprise the sequential stages presented in Figure 1: acquisition of a standardized image, automatic recognition of the tooth, segmentation of the surface, exclusion of specular highlights, color calibration, transformation of color coordinates, analysis of individual tooth regions, determination of the closest shade, generation of a digital color map, and transfer of the data to a CAD/CAM system or dental laboratory.

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Figure 1

Proposed Integrated Workflow for Digital Tooth Shade Determination



Note. ROI = region of interest; ΔE00 = color difference calculated with the CIEDE2000 formula; L* = lightness; C* = chroma; h = hue angle; CAD/CAM = computer-aided design and computer-aided manufacturing. Solid arrows indicate the sequential processing pathway; the dashed pathway indicates external validation of algorithm output on independent clinical data and subsequent model refinement. The workflow synthesizes the standardization requirements described by Hina et al. (2024), Lazar et al. (2019), and Rashid et al. (2023) with the automated processing stages reported by Shetty et al. (2024) and Tao et al. (2026).

The application of artificial intelligence may reduce operator involvement at individual stages and potentially increase the reproducibility of results.

The development of software solutions that do not require a separate, costly device is of particular interest. The use of a standard digital camera or a smartphone camera together with a calibration reference and validated software could potentially make objectified color determination more accessible; the results reported by Tao et al. (2026) for device-agnostic algorithms support the feasibility of this direction.

A further promising direction is the transition from the determination of a single tooth shade to the construction of a digital color map. Such a map may contain data on the lightness, chroma, hue, and translucency of different regions of the crown, which is considerably more informative than a single designation from a standard shade guide.

The introduction of such systems requires standardized capture protocols, unified requirements for color calibration, the creation of large clinical image databases, and independent external validation of the algorithms developed.

Conclusions

1. Digital technologies allow a considerable increase in the objectivity and reproducibility of tooth shade determination compared with purely visual assessment; the accuracy of different digital methods is, however, not uniform.

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2. Spectrophotometry remains the best-substantiated instrumental reference method for determining the color of natural teeth and is widely used to evaluate the accuracy of other digital technologies.
3. Digital photography possesses considerable potential owing to the possibility of analyzing the entire tooth surface, documenting the result, and processing the image by software. Its clinical accuracy depends directly on the standardization of capture and on color calibration.
4. Intraoral scanners provide convenient integration of shade determination into the digital CAD/CAM protocol and are characterized by high repeatability; their trueness in determining color nevertheless depends on the particular system and does not always correspond to spectrophotometric data.
5. A promising direction is the development of software systems that combine standardized image acquisition, automated color calibration, analysis of individual tooth regions, and artificial intelligence algorithms.
6. The introduction of artificial intelligence systems for shade determination into broad clinical practice requires standardized datasets, external validation of algorithms, and studies of their effectiveness under real clinical conditions.

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