Application of Photoacoustic System for Caries Detection: Systematic Review

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ABSTRACT

This research was done in the form of a thorough assessment of the systematic review on the application of photoacoustic methods to detect dental caries. This paper also reviews the broader applications of photoacoustic techniques in dentistry, beyond their use in detecting specific dental diseases. The method employed in this review paper begins with the identification of relevant studies, followed by screening and eligibility assessment. Finally, the selected articles are ready for comprehensive review. Out of 2,940 papers initially considered, only seven were accepted for analysis. This selection was based on several criteria that have been set for reviewing the articles. It was evident that only three out of the seven articles focused on the issue of dental caries. The review recommends two things for future studies. First, it suggests using qualitative studies for detecting caries lesions because they provide detailed and in-depth insights for dentists to make informed treatment decisions. Second, it anticipates a high demand for new technology that is non-invasive, radiation-free, and handheld for detecting caries lesions, as such technology does not currently exist.

Keywords: Photoacoustic, Caries, Non-invasive, Dental, Technology

1. Introduction

About half of the world population (3.5 billion) have some kind of oral health problems [1]. The World Health Organization (WHO) defines oral health as “the absence of diseases that impair a person's capacity to bite, chew, smile, and talk, such as periodontal disease, oral infections and sores, oral and throat cancer, tooth decay, and tooth loss”. These diseases not only affect a specific area in the oral cavity but also have broader implications to the overall well-being of an individual. Oral diseases may affect both dental health and the body's general functioning, thus it has been recognized as a major public health problem [2]. Dental caries, periodontal disease, loss of teeth, and mouth cancer are common oral diseases that can be prevented. Despite being avoidable, these ailments rank among the most widespread noncommunicable diseases globally, causing significant health, social, and economic consequences.

Dental caries and periodontal diseases are the most prevalent oral health conditions. Globally, untreated dental caries impacts 2.3 billion individuals, while severe gum disease affects 267 million people, often leading to tooth loss, particularly among the elderly [3]. Dental caries is a microbial infection impacting teeth, causes localized dissolution and damage to the calcified tissues [4]. Meanwhile, peridontal disease refers to a variety of inflammatory disorders that lead to the destruction of the gums, periodontal ligament, cementum, and alveolar bone, which are tissues supporting teeth [5].

Dental caries ranks as the second most common reason for tooth loss, and high prevalent across various demographics. When dental caries progresses, it can be extremely painful, and expensive to treat because more complex treament require. Despite these difficulties, some preventive measures can be reasonably effective [4]. Dental caries, another name for tooth decay, is an ailment caused by bacteria causing demineralization and harm to the tooth's mineralized structures. Dental plaque, bacteria, tooth structure, and time are all factors involved in the process of caries formation. Plaque accumulation is the first step, attracting bacteria that produce acid, such as Actinomyces viscosus and Streptococcus mutans. This plaque provides a platform for bacteria to manufacture lactic acid when it comes into contact with carbohydrates found in diet. The tooth releases both phosphate and calcium ions as a result of the electrochemical changes brought on by this acid. Regularly consuming sugary foods worsens the demineralization, damaging the tooth's organic matrix. On the contrary, diets rich in dairy, fish, meats, and polyphenols are seen as preventive measures against dental caries [6].

The American Dental Association's Caries Classification System (CCS) provides the foundation for the visual and tactile technique that dentists most frequently utilize to detect cavities which is has been outlined in their guidelines by Young et al. [7]. The International Caries Detection and Assessment System (ICDAS) was created to offer a trustworthy framework for consistent caries diagnosis and detection across a range of contexts to epidemiologists, researchers, and healthcare professionals. ICDAS presents a novel approach to dental caries assessment, developed from ideas gleaned from a thorough literature analysis of clinical caries detection methods and other relevant sources as shown in Table 1 [8].

Few techniques or approach had been commercialize such as intraoral radiograph, near infrared translumination, light induced fluorenscne, laser fluoresncne and electrical conductivity. These techniques had its own drawbacks as shown in Table 2.

Table 1. ICDAS II codes and criteria (Gupta et al., 2011)

Code	Description
0	Sound tooth surface: After five seconds of air drying, no signs of cavities were seen.
1	First visual change in enamel: After a long period of air drying, opacity or discolor (white or brown) is noticeable around the pit or fissure's entry.
2	When wet, there must be a noticeable change in the enamel's appearance; the lesion must still be evident when dry.
3	Restricted loss of enamel in a particular area (without obvious clinical signs of dentinal involvement), observable both while wet and after a long drying period.
4	Noticeable dark dentine shadow.
5	Noticeable cavity with visible dentine.
6	Large cavity with visible dentine that covers over fifty percent of the surface

Table 2. Latest techniques and its drawbacks

Technique	Drawbacks
Intraoral radiographs	• Before appearing on radiography, 30–40% of enamel needs to demineralize. (eliminating early caries stages). [9]. • There are two types of radiation exposure: digital (lower radiation) and analog (higher radiation). [10], [11]
Near-Infrared Transillumination (NIRT)	• There may be some proximal caries that are invisible [9]. • The first lower primary molars are very difficult to visualize. [9].
Light-induced Fluorescene (LF)	• A false positive result could result from contamination such as blood, calculus, or plaque interfering with carious lesions. Inexperienced staff may overtreat as a result [9].
Laser Fluorescene	• More accurate in determining a caries' volume than its depth within the tooth [12]. • Extremely costly [12].
Electrical Conductivity	• Time-consuming to perform routine full mouth examinations [12]. • Provides no evidence of either active or inactive cavities. [12].

Therefore, in order to overcome the problem of caries lesion, this review paper examines ways of early detection using photoacoustics techniques. A hybrid non-invasive imaging technique called photoacoustic tomography (PAT) combines excellent ultrasonic resolution with rich optical contrast in murky tissue. Through the process of separating various imaging metrics from the photoacoustic signals, the PAT is able to provide an accurate representation of various biochemical data, biomechanical attributes, microstructural features, blood flow, temperature distribution, and more. Furthermore, compared to ionizing radiation sources like X-rays, which are employed as radiographic methods for dental examinations in clinics, PAT's non-ionizing laser is far safer [13].

In PAT, tissue chromophores absorb photons from pulsed lasers, and either all or some of the photons' energy is transformed into heat. The brief spike in temperature causes an increase in pressure, which in turn causes the production of sound waves. The local optical fluence and chromophore concentration are intimately correlated with the sound wave's strength and the pressure increase's amplitude. After that, the sound wave is picked up by an ultrasonic transducer, which creates an image that is used to tomographically map the tissue's initial energy deposition [14].

2. Methodology

In this section, the approach used to gather information from previous studies concerning the application of photoacoustic techniques in dentistry had been discussed. The reviewers utilized the PRISMA 2020 method [15] [16], [17]. Figure 1 shows the overall flow on how searching process had been done. It is important to clarify that this systematic literature review (SLR) focuses solely on photoacoustic methods discussing caries lesions detections

2.1 Resources

This review was conducted using two avalaible databases, namely Scopus, which serves as the primary database for this review. Scopus is the largest database utilized, encompassing over 22,800 journals from 5,000 publishers worldwide, based on an abstract and reference database of literature with peer review. Scopus covers a broad range of subject areas, including biomedical engineering, science, and technology. The second database used is ProQuest, which boasts partnerships with more than 9,000 publishers and content providers. ProQuest is also a part of Clarivate, a company known for leading research and education. Clarivate's portfolio includes Web of Science, ProQuest, Ex Libris, and Innovative.

2.2 Systematic searching strategies

The systematic searching strategies were introduced by Shaffril et. al. [16] comprising three levels of review: identification, screening, and eligibility. Afterward, the articles are prepared for the reviewing process. This approach can simplify the process for reviewers, enabling them to analyze the articles more effectively.

Table 3. String used in search engine at respective database

Database	String
Scopus	TITLE-ABS-KEY ((“photoacoustic" OR "photoacoustic tomography*" OR "photoacoustic imag*" OR "photoacoustic technique*”) AND (“dental" OR "dentist*" OR "dentistry”))
ProoQuest	((“photoacoustic" OR "photoacoustic tomography*" OR "photoacoustic imag*" OR "photoacoustic technique*”) AND (“dental" OR "dentist*" OR "dentistry”))

1) *Identification:* In the identification phase, reviewers utilized the search engine within the database, employing specific keywords. For instance, terms like "photoacoustic tomography" were considered synonymous with "photoacoustic imaging” and “photoacoustic technique”. Additionally, given the focus of this article on the application of photoacoustic techniques in dentistry, related keywords such as "dental" and "dentist" were incorporated. The search strings in both databases involved the use of Boolean operations, functions, truncation, and phrase searching, as detailed in Table 3. The combined keywords yielded a total of 2,940 sources, as illustrated in Figure 1.

2) *Screening:* Next, screening represents the second step in the systematic searching strategies. In the screening process, several criteria are applied for inclusion or exclusion. For this review paper, four inclusion criteria will be considered based on Table 4. Firstly, the review is confined to the period from 2019 to 2024. Consequently, sources from 2018 and earlier are excluded. This approach aligns with the concept of research field maturity, as suggested by [17]. Given the rapid advancements in technology, a five-year time frame was selected to ensure the review captures the most current practices and developments. The authors have also decided to exclusively select articles, books, and conference proceedings for inclusion in this review paper. Any review articles are excluded from consideration.

   Furthermore, only sources in the English language are included, with non-English sources being excluded. Given that the objective of the systematic literature review (SLR) is to examine previous studies related to photoacoustic techniques in dentistry, the subject area is strictly limited to the fields of engineering and dentistry. Consequently, sources from non-engineering and non-dental fields are excluded such as medicine, pharmacy,

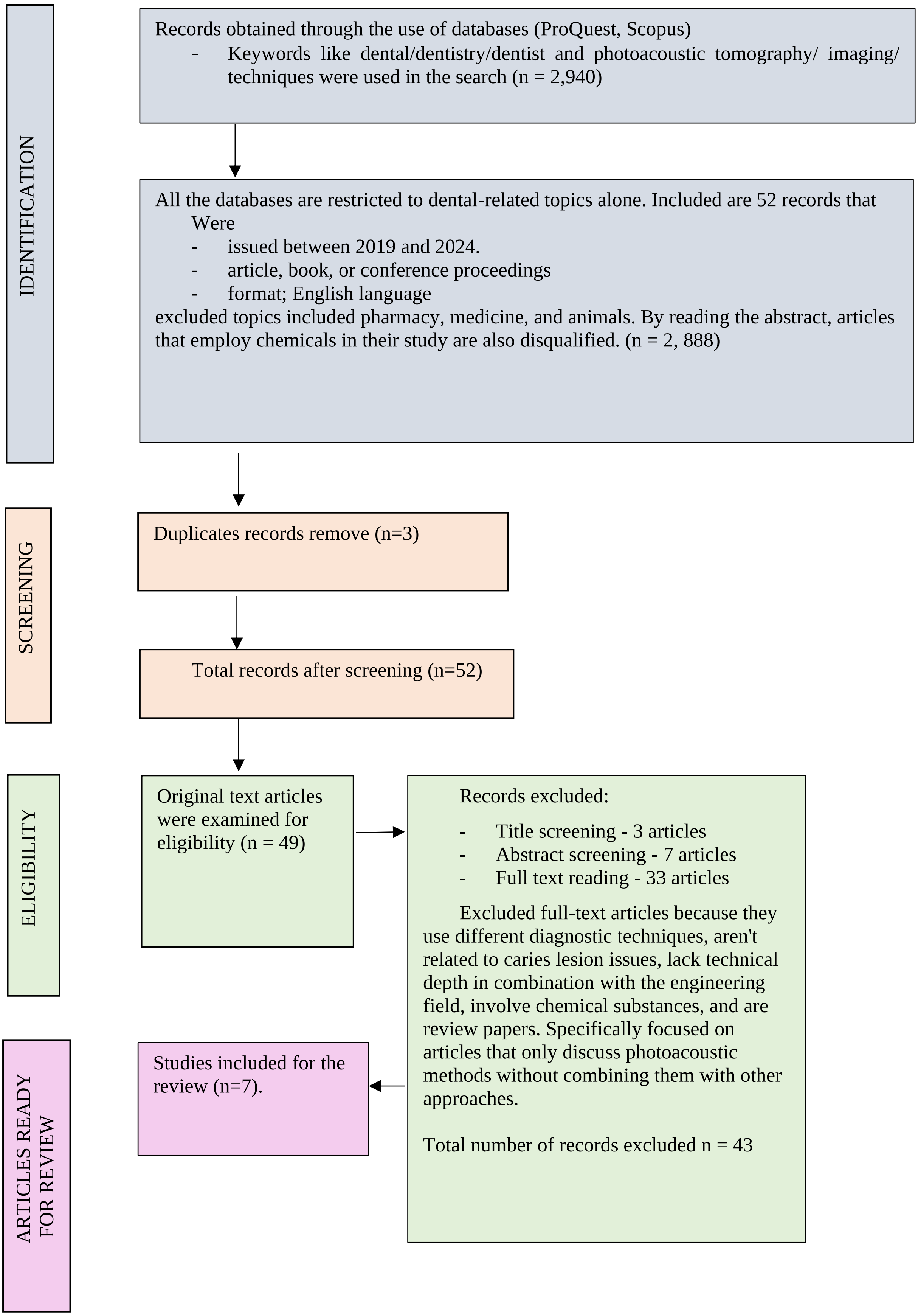

Figure 1. The flow diagram of searching

Table 4. Inclusion and exclusion based on four criterions

Criterion	Inclusion	Exclusion
Year	2019-2024	2018 and earlier
Document types	Articles, book and conference proceedings	Review article
Language	English	Non-English
Subject area	Engineering and dentistry	Non-engineering

animal and a lots of chemical substances usage throughout the research. Therefore, the total number of accepted sources after screening is 52 (see Figure 1).

3) *Eligibility:* In this section, the authors evaluated articles based on title and abstract screening, as well as full-text reading. Three articles were excluded during title screening, followed by the exclusion of seven articles during abstract screening. During full-text reading, 33 articles were excluded. The exclusion criteria encompassed articles that used different diagnostic techniques, lacked relevance to caries lesion issues, lacked technical depth when combined with the engineering field, involved chemical substances or articles discussing photoacoustic methods without combining them with other approaches. Consequently, the total number of excluded records was 43 and only seven articles eligible for review.

The seven articles were analyzed based on eight types of classification, which are the experimental setting (in-vivo, ex-vivo, in-vitro), focus area, wavelength, software used, types of transmitters and receivers, output, and the overall discussion of each paper. These aspects were chosen because they represent critical factors necessary for a comprehensive analysis of the studies. The experimental setting (in-vivo, ex-vivo, in-vitro) is essential to understand the context and environment in which the experiments were conducted. The focus area highlights position of teeth or the caries being examined, while the wavelength and software used are crucial for evaluating the technical parameters and methodologies. The types of transmitters and receivers are key components in many experimental setups, and the output reflects the results and findings. Lastly, the overall discussion provides a deeper understanding of the conclusions drawn in each study, offering a holistic view of their contributions to the field.

3. Result and Discussion

Review of the seven sources that have been selected, eight types of classification have been set as outlined in Table 5. These eight classifications include experiment setting (with three subsections), focus area, wavelength, software (with two subsections), transmitter, receivers, output, and discussion. The results from Table 5 facilitate a clearer analysis of the current photoacoustic techniques in caries detection and other unspecified dental conditions.

3.1 Experiment setting

Out of seven studies, only one article [13] conducted a study solely based on simulation. Meanwhile, the other six sources are based on three types of experimental settings, namely in-vivo, ex-vivo [18], [19], [20], [21], [22] , and in vitro [18], [19], [20], [21], [22], [23]. In general, it is clear that the majority of experimental settings involve in ex-vivo setups. Only one study conducted the research by in vitro setup.

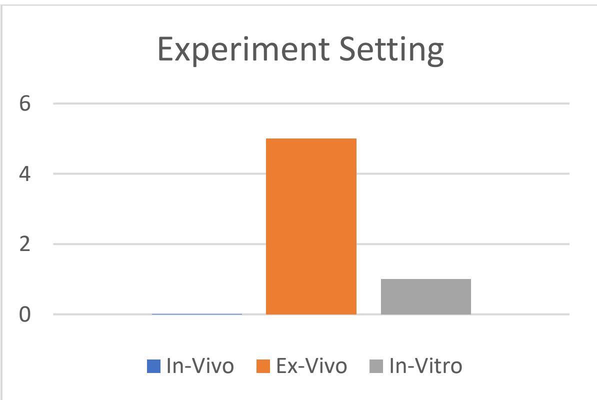

Figure 2. Experiment setting based on selected studies

Indirectly, there is still no study that indicates and conducts experiments through in-vivo setup. The in-vivo method can speed up and save the time of dentists [24]. This is crucial because, in order to assess the condition of carious teeth, the in-vivo method of study is recommended because practitioners can directly identify caries lesion using free radiation, non-invasive and handheld technology. A clear chart in Figure 2 illustrates the respective total number of experiments in in-vivo, ex-vivo, and in-vitro settings.

3.2 Focus area

Various focus areas have been explored in the examination of all seven studies. Among them, some studies investigated on hidden caries [21] and the severity level of caries issues [20], as well as early detection of caries lesions [13].

Additionally, certain studies have concentrated on specific parts of the teeth to be examined, such as premolars, molars, and anterior teeth [19]. In one case, the study focused on human mandibular incisors [23] while another examined molar teeth, including enamel, dentin, and pulp [18].

3.3 Types of transmitters and its wavelength

In this review paper, the wavelength of the transmitter is identified as an important parameter for setting up experiments as the input source. Upon analysis, it is noted that 4 out of 7 studies use a diode laser as the transmitter, and the common wavelength employed is 532 nm [18], [20], [21], [22]. However, in the article by [20], the study focuses on comparing two wavelengths, namely 532 nm and 1064 nm. This research specifically investigates the reconstruction of photoacoustic images and the depth measured obtained based on both wavelengths.

Tasmara's investigation used a wavelength of 532 nm. It has been stated that this technology may accurately identify hidden cavities and distinguish between healthy and carious teeth based on the acoustic intensity level detected by the contact of teeth with laser light.

Additionally, two studies examine the use of laser light as a transmitter, employing various wavelength values to assess the effects of these differences [19], [23]. A comparison between the use of laser and LED has been concluded by [20] indicating that LED is superior to laser in the application of photoacoustic imaging techniques. Meanwhile, another study by [13] has been conducted to examine the differences between a broad beam light source and a pencil beam light source for detecting caries, utilizing the same wavelength of 633 nm. The conclusion drawn from this study indicates that for the early detection of tooth lesions using photoacoustic imaging, the use of a broad beam light source is better compared to a pencil beam light source.

3.4 Types of receivers and software use

Majority of studies related to the photoacoustic technique utilize condenser microphones as their receivers [18], [21], [22]. However, one study employs a photoacoustic detector as the receiver [20], while the receiver type remains unspecified in two other studies [19], [23]. In [13] simulation-based research, output readings are generated using both Monte Carlo and K-Wave MATLAB.

Furthermore, studies performing experiments in-vivo, ex-vivo, and in-vitro leverage various software tools like LabVIEW [18], [20], [21], Python ([21], Cubify design, ImageJ2 [23] and CLINIVIEW [20]. Additionally, statistical analysis software such as OriginPro [21], SPSS [19], Kruskal-Wallis-Test, post-hoc Mann-Whitney U-test and Mann–Whitney post-hoc test [22], [23] is employed for clear data presentation.

3.5 Output

Among the seven mentioned studies, each has a distinct output corresponding to its specific research objectives. Tasmara et al. and Afikalaila et al. [18], [21] both investigated the same output parameter, namely acoustic intensity level in decibel (dB) However, their research objectives differed, with focusing on caries detection by Tasmara's study [21] and examining the characterization of dental anatomy by Afikalaila's study [18]. Chan's study, [19], on the other hand, explored light penetration into the teeth, with the evaluated output being the average attenuation coefficient (μ)

The research by Schneider et al. (2022) delved into outputs based on volume and surface deviations, utilizing two different wavelengths [23]. The primary aim of this study was to determine the most effective wavelength for Photoacoustic Tomography (PAT) while also assessing the depth of tooth image reconstruction. In contrast, Silva et al. (2021) work focused on caries detection, with the output centered on Weber contrast value [20]. Widyanigrum et al. 2020 aimed to evaluate the quality of images produced through photoacoustic imaging [22], and Arabpou et. al. (2019) investigated caries in teeth, measuring output based on two parameters: Mean of absorbed energy (W/m2) and mean of pressure (Pascal) [13].

It is evident that only three of these studies [13], [20], [21] primarily aimed to investigate caries detection. However, the outputs from these three researchers differ significantly. Tasmara et. al measured acoustic intensity level (dB)[21], Silva et.al examined Weber contrast value [20], and Arabpou et al. assessed mean of absorbed energy (W/m2) and mean of pressure (Pascal) [13].

Table 5. The findings based on 8 main themes

Author	**Experiment setting**			**Focus area**	**λ (nm)**	**Software**		**TX**	**RX**	**Output**	**Discussion**
	IV	**EV**	**VT**			**S**	**SI**				
Tasmara et. al. [21]		■		Hidden carries	532	- LabVIEW - Python	OriginPro	Diode laser (Nd: YAG laser)	Condenser microphone	Acoustic intensity level (dB)	Caries detection
Chan et. al. [19]		■		Premolars, molars and anterior teeth	450 650 810 980		SPSS	Laser light		Average attenuation coefficients (μ)	Light penetration through tooth
Schneider et. al. [23]			■	Human mandibular incisor	680 960	-Cubify design -ImageJ2	-Kruskal WallisTest -Post-hoc Mann-Whitney U-test.	Laser light		Volume and surface Deviations	Best wavelength for PAT and how deep image reconstruction of tooth
Afikalaila et. al. [18]	Not mention			Molar teeth (enamel, dentin, and pulp)	532	LabVIEW		Diode laser	Condenser microphone	Acoustic Intensity (dB)	Characterization of dental anatomical
Silva et. al. [20]	Not mention			Incipient and advanced caries	532 1064	-CLINIVIEW -LabVIEW		Diode laser (Nd: YAG laser)	PA detector	Weber contrast values	Caries detection
Widyaningrum et. al. [22]		■			532		-Kruskal–Wallis test -Mann–Whitney post-hoc test	CW diode laser	Condenser microphone	Image quality	PA image quality
Arabpou et. al. [13]	Not mention			Early detection caries	633	-Monte Carlo -K-Wave MatLAB		-Broad beam light source -Pencil beam light source		-Mean of absorbed energy (W/m2) -Mean of pressure (Pascal)	Caries detection
IV = In- Vivo EV = Ex-Vivo VT = In-Vitro				Λ = wavelength nm = nanometer S = software			St = Statistical software & method TX = Transmitter RX = Receiver				

4. Conclusion

The range of wavelengths employed among the seven papers reviewed was between 450 nm and 1064 nm. It was also found that the 532 nm wavelength was the most frequently used. Therefore, further studies on this range of wavelengths could be conducted to delve deeper into their impact on image quality for detecting caries and the suitability of these wavelengths in the dental field. These review papers recommended a few approaches for future studies; first, future studies should integrate quantitative and qualitative approaches for caries detection. This combination can provide comprehensive insights, with quantitative 3D imaging measuring caries depth and volume, complemented by qualitative assessments of lesion severity. Hence, they provide detailed explanations and in-depth analyses. These studies offer and provide dentists with valuable insights for making diagnosis and informed decisions regarding treatment. Second, technology that is non-invasive, radiation-free, cost-effective and handheld in detecting caries lesions were suggested. This is because the product of such technology mentioned is expected to be in high demand in the market, as such the development of the technology is limited.

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