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MANUAL, SONIC, AND ULTRASONIC IRRIGATION ACTIVATION IN ROOT CANAL DISINFECTION: A SYSTEMATIC REVIEW OF SMEAR LAYER REMOVAL AND ANTIBACTERIAL EFFICACY

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Abstract

Background:
Effective root canal disinfection remains a major challenge in endodontic therapy because of the complex anatomy of the root canal system and the persistence of microorganisms within inaccessible areas. Various irrigation activation techniques, including manual dynamic agitation, sonic irrigation, and ultrasonic irrigation, have been developed to improve smear layer removal and antibacterial efficacy. This systematic review aimed to compare the effectiveness of these irrigation activation methods in enhancing root canal cleanliness and reducing bacterial load.

Methods:
A comprehensive literature search was conducted across PubMed, Scopus, Web of Science, and Google Scholar from inception until May 2026. Studies comparing at least two irrigation techniques, including manual, sonic, ultrasonic, or conventional syringe irrigation, were included. Primary outcomes assessed were smear layer removal, debris elimination, and bacterial reduction. Quality assessment was performed using the Cochrane Risk of Bias 2 tool for randomized clinical trials and the Joanna Briggs Institute checklist for ex vivo studies.

Results:
A total of 2,184 studies were identified, of which six met the eligibility criteria. These included two randomized clinical trials and four ex vivo studies. Activated irrigation systems consistently demonstrated superior performance compared with conventional syringe irrigation. Sonic irrigation showed effective smear layer removal, particularly in the apical third, while passive ultrasonic irrigation demonstrated greater dentinal tubule cleanliness and superior antibacterial efficacy. Clinical studies also reported greater bacterial reduction and reduced postoperative pain with ultrasonic activation.

Conclusion:
Sonic and ultrasonic irrigation activation techniques demonstrated superior effectiveness in smear layer removal and bacterial reduction compared with conventional irrigation methods. Incorporating activated irrigation systems into routine endodontic practice may improve root canal disinfection and treatment

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outcomes. Further well-designed randomized clinical trials are required to establish standardized clinical protocols.

Introduction

The root canal system is a highly complex anatomical structure composed of the pulp chamber and an intricate network of canals containing vascular, neural, and connective tissues. The integrity of this system is essential for maintaining tooth vitality and function. However, when dental caries progress beyond the enamel and dentin layers without timely intervention, microorganisms gain access to the pulp tissue, initiating inflammatory and infectious processes within the canal system. Persistent microbial invasion may lead to irreversible pulpitis, pulp necrosis, and eventually apical periodontitis if left untreated [1]. The progression of infection within the root canal system creates an environment favorable for bacterial colonization, biofilm formation, and tissue degradation, making complete disinfection a critical objective in endodontic therapy.

Root canal treatment is primarily aimed at eliminating infected pulp tissue, reducing microbial load, and sealing the root canal system to prevent reinfection. This is achieved through chemo-mechanical preparation, which combines mechanical instrumentation with chemical irrigation to remove necrotic tissue, microorganisms, and organic debris. Despite significant advancements in endodontic instruments and materials, complete microbial eradication remains one of the most challenging aspects of root canal therapy. One of the major reasons for this challenge is the anatomical complexity of the root canal system, including isthmuses, fins, lateral canals, accessory canals, and apical ramifications, which can hinder the effective penetration of irrigating solutions and mechanical instruments [2].

Microbial persistence within inaccessible areas of the canal system has been strongly associated with endodontic treatment failure. Bacteria can invade dentinal tubules and survive in protected anatomical niches where conventional instrumentation cannot effectively reach. These microorganisms may persist even after canal preparation and later contribute to reinfection or persistent periapical inflammation [3]. Therefore, irrigation protocols play a fundamental role in enhancing root canal disinfection by facilitating the penetration of antimicrobial solutions into anatomically complex regions.

Another important challenge during root canal preparation is the formation of the smear layer. The smear layer is an amorphous layer of organic and inorganic debris created on canal walls during instrumentation. It consists of dentin particles, remnants of pulp tissue, collagen fibers, blood cells, and microorganisms, which become compacted along the canal surface and may extend into dentinal tubules as smear plugs [4]. The presence of the smear layer has significant clinical implications, as it can act as a physical barrier that reduces the penetration of irrigants, intracanal medicaments, and obturation materials into dentinal tubules. Additionally, it may serve as a reservoir for residual bacteria, increasing the risk of reinfection after treatment [3].

Conventional syringe irrigation has long been considered the standard irrigation method in endodontics because of its simplicity, affordability, and widespread availability. Typically, solutions such as sodium hypochlorite and ethylenediaminetetraacetic acid (EDTA) are delivered into the root canal under positive pressure through a syringe and needle. Although this technique can effectively flush out loose debris and provide antimicrobial action, its effectiveness is often limited in complex root canal anatomy because of restricted irrigant penetration, vapor lock formation, and insufficient fluid exchange in the apical region [5]. These limitations have driven the development of irrigant activation techniques aimed at improving the distribution and effectiveness of irrigating solutions.

Among the most commonly investigated activation techniques are manual dynamic agitation, sonic activation, and ultrasonic activation. Manual dynamic agitation enhances irrigant movement through repeated insertion and withdrawal of gutta-percha cones or hand

Frontier in Medical & Health Research
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instruments. Sonic irrigation operates at lower frequencies and creates hydrodynamic agitation that improves irrigant exchange and debris displacement. In contrast, ultrasonic irrigation utilizes higher frequencies, generating acoustic streaming and cavitation effects that significantly enhance irrigant penetration, biofilm disruption, and smear layer removal [6]. Several experimental and clinical studies have compared these activation techniques with conventional syringe irrigation, reporting varying results regarding their effectiveness in bacterial reduction and canal cleanliness.

Although numerous studies have investigated irrigation activation systems, the available evidence remains inconsistent because of differences in study design, sample characteristics, outcome measures, and irrigation protocols. Some studies suggest superior performance of ultrasonic activation, whereas others report comparable outcomes between sonic and manual activation systems. Additionally, previous investigations often evaluated either bacterial reduction or smear layer removal independently rather than examining both outcomes collectively.

Therefore, this systematic review aims to comprehensively compare the effectiveness of manual, sonic, and ultrasonic irrigation activation techniques in reducing bacterial load and removing the smear layer during root canal treatment. By synthesizing available evidence from clinical and experimental studies, this study seeks to provide stronger evidence regarding the most effective irrigation activation strategy for improving endodontic treatment outcomes.

Search Strategy

A comprehensive and systematic literature search was conducted to identify relevant studies comparing the effectiveness of different irrigation activation techniques in endodontic treatment. Electronic databases including PubMed, Scopus, Web of Science, and Google Scholar were searched from their inception until May 2026. The search strategy was developed using a combination of Medical Subject Headings (MeSH) terms and free-text keywords related to root canal irrigation and activation techniques. Search terms included "root canal irrigation," "endodontic irrigation," "irrigant activation," "passive ultrasonic irrigation," "sonic irrigation," "manual dynamic agitation," "conventional irrigation," "bacterial reduction," "smear layer removal," and "debris removal." Boolean operators such as AND and OR were used to combine search terms appropriately. In addition to the electronic database search, the reference lists of all eligible studies were manually screened to identify any additional relevant articles.

Study Selection

All studies identified through the database search were exported into reference management software, and duplicate records were removed before screening. Two independent reviewers screened the titles and abstracts of all retrieved studies according to predefined eligibility criteria. Studies that appeared relevant were selected for full-text review. Full-text articles were then assessed carefully for final inclusion in the systematic review. Studies were included if they compared at least two irrigation activation techniques, including ultrasonic, sonic, manual, or conventional irrigation methods, and reported outcomes related to bacterial reduction, smear layer removal, or debris removal. Randomized clinical trials, comparative clinical studies, and ex vivo or in vitro experimental studies were considered eligible for inclusion. Review articles, meta-analyses, case reports, editorials, conference abstracts, and studies lacking relevant outcome data were excluded. Any disagreements between the reviewers during the selection process were resolved through discussion until consensus was achieved.

Data Extraction

Data extraction was performed independently by two reviewers using a standardized data extraction form designed specifically for this systematic review. Relevant information was collected from each included study, including the first author's name, year of publication, country of origin, study design, sample size, type of teeth or participants included, irrigation activation techniques used, irrigating solutions, outcome assessment methods, and main findings. Particular emphasis was placed on extracting data related to bacterial reduction, smear layer removal, and debris removal, as these were the primary outcomes of interest. Additional methodological details, such as duration of irrigation activation, type of ultrasonic or sonic devices used, and evaluation methods including scanning electron microscopy or microbiological analysis, were also recorded when available. Any discrepancies in the extracted data between the two reviewers were resolved through discussion and mutual agreement to ensure accuracy and consistency in the final dataset.

Risk of Bias and Quality Assessment

The methodological quality of the included studies was assessed according to the study design of each article. The two randomized clinical trials were evaluated using the Cochrane Collaboration Risk of Bias 2 (RoB 2) tool, while the ex vivo experimental studies were assessed using an adapted Joanna Briggs Institute critical appraisal checklist.

Among the randomized clinical trials, both Orozco et al. (2020) and Palanisamy et al. (2023) demonstrated an overall low risk of bias across most assessed domains, including randomization process, outcome measurement, and selective reporting. However, some concerns were observed in allocation concealment and sample size reporting.

Among the ex vivo studies, Khaord and Amin (2015), Mozo et al. (2014), and Machado et al. (2021) demonstrated high methodological quality due to clearly defined experimental protocols, standardized instrumentation procedures, and objective outcome assessment using scanning electron microscopy. However, Kato et al. (2016) showed moderate methodological quality because of limited sample size and incomplete reporting of operator blinding procedures. Overall, the included studies demonstrated acceptable methodological quality, with most studies presenting low risk of bias and reliable outcome assessment.

The detailed risk of bias assessment of the randomized clinical trials is presented in Figure 2, while the methodological quality assessment of the ex vivo studies is summarized in Figure 3. The overall quality assessment of all included studies is presented in Figure 4.

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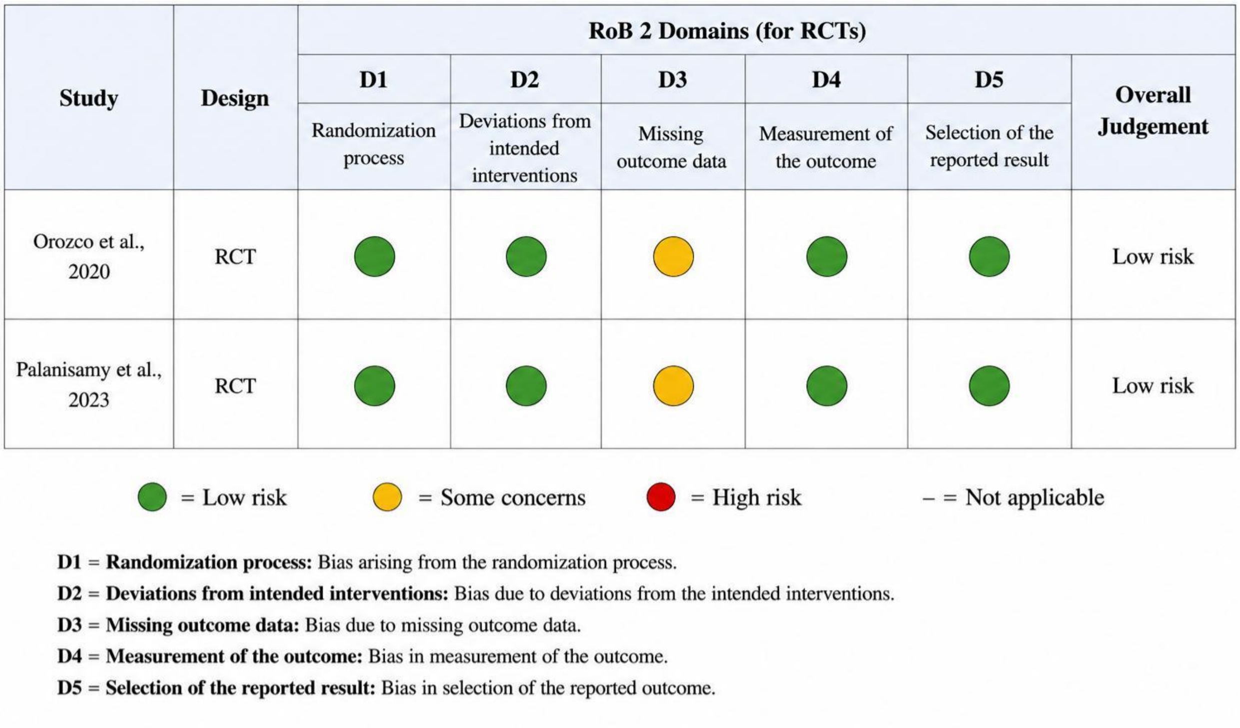
Figure 2
Risk of Bias Assessment of Randomized Clinical Trials Using the RoB 2 Tool
Figure 3

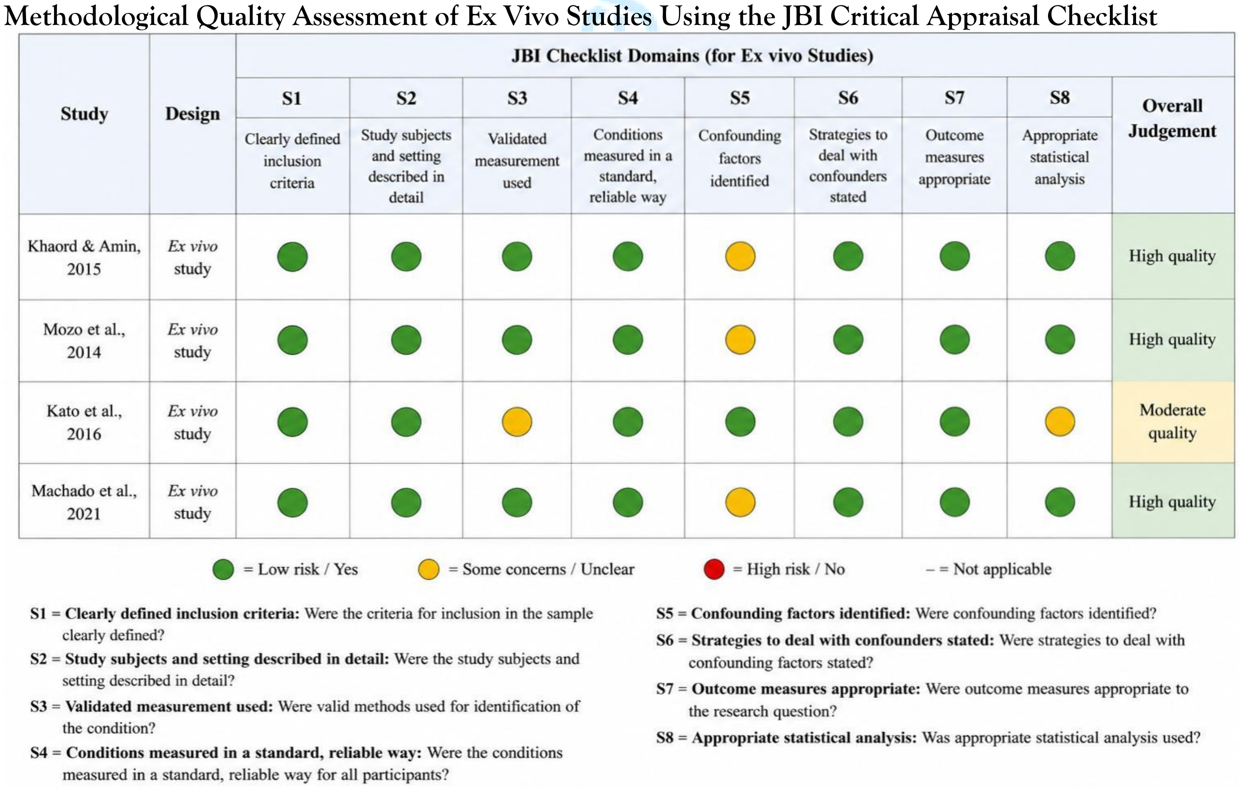


Study	Design	RoB 2 Domains (for RCTs)					
		D1	D2	D3	D4	D5	Overall Judgement
		Randomization process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	
Orozco et al., 2020	RCT	🟢	🟢	🟡	🟢	🟢	Low risk
Palanisamy et al., 2023	RCT	🟢	🟢	🟡	🟢	🟢	Low risk

🟢 = Low risk 🟡 = Some concerns 🔴 = High risk – = Not applicable

D1 = Randomization process: Bias arising from the randomization process.
D2 = Deviations from intended interventions: Bias due to deviations from the intended interventions.
D3 = Missing outcome data: Bias due to missing outcome data.
D4 = Measurement of the outcome: Bias in measurement of the outcome.
D5 = Selection of the reported result: Bias in selection of the reported outcome.

Methodological Quality Assessment of Ex Vivo Studies Using the JBI Critical Appraisal Checklist



Study	Design	JBI Checklist Domains (for Ex vivo Studies)								
		S1	S2	S3	S4	S5	S6	S7	S8	Overall Judgement
		Clearly defined inclusion criteria	Study subjects and setting described in detail	Validated measurement used	Conditions measured in a standard, reliable way	Confounding factors identified	Strategies to deal with confounders stated	Outcome measures appropriate	Appropriate statistical analysis	
Khaord & Amin, 2015	*Ex vivo* study	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	High quality
Mozo et al., 2014	*Ex vivo* study	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	High quality
Kato et al., 2016	*Ex vivo* study	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟡	Moderate quality
Machado et al., 2021	*Ex vivo* study	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	High quality

🟢 = Low risk / Yes 🟡 = Some concerns / Unclear 🔴 = High risk / No – = Not applicable

S1 = Clearly defined inclusion criteria: Were the criteria for inclusion in the sample clearly defined?
S2 = Study subjects and setting described in detail: Were the study subjects and setting described in detail?
S3 = Validated measurement used: Were valid methods used for identification of the condition?
S4 = Conditions measured in a standard, reliable way: Were the conditions measured in a standard, reliable way for all participants?
S5 = Confounding factors identified: Were confounding factors identified?
S6 = Strategies to deal with confounders stated: Were strategies to deal with confounding factors stated?
S7 = Outcome measures appropriate: Were outcome measures appropriate to the research question?
S8 = Appropriate statistical analysis: Was appropriate statistical analysis used?

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Figure 4

Overall Quality Assessment of Included Studies

Study	Study Design	Quality Assessment Tool Used	Overall Judgment
Orozco et al., 2020	Randomized clinical trial	RoB 2	✓ Low risk
Palanisamy et al., 2023	Randomized clinical trial	RoB 2	✓ Low risk
Khaord & Amin, 2015	*Ex vivo* study	JBI Checklist	✓ High quality
Mozo et al., 2014	*Ex vivo* study	JBI Checklist	✓ High quality
Kato et al., 2016	*Ex vivo* study	JBI Checklist	– Moderate quality
Machado et al., 2021	*Ex vivo* study	JBI Checklist	✓ High quality

✓ Low risk / High quality – Moderate quality ✗ High risk / Low quality

Note: RoB 2 was used for randomized clinical trials; JBI Checklist was used for ex vivo studies.

Results

The systematic literature search across electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar, initially identified 2,184 records. After removal of duplicate studies (n = 624), a total of 1,560 records remained for title and abstract screening. During the initial screening phase, 1,432 studies were excluded because they did not meet the predefined eligibility criteria. The full texts of 128 potentially relevant studies were assessed for eligibility. Following full-text evaluation, 122 studies were excluded due to irrelevant population, inappropriate intervention, lack of relevant outcome measures, or insufficient methodological data. Finally, 6 studies met all inclusion criteria and were included in the qualitative synthesis. The study selection process is presented in Figure 1 (PRISMA flow diagram).

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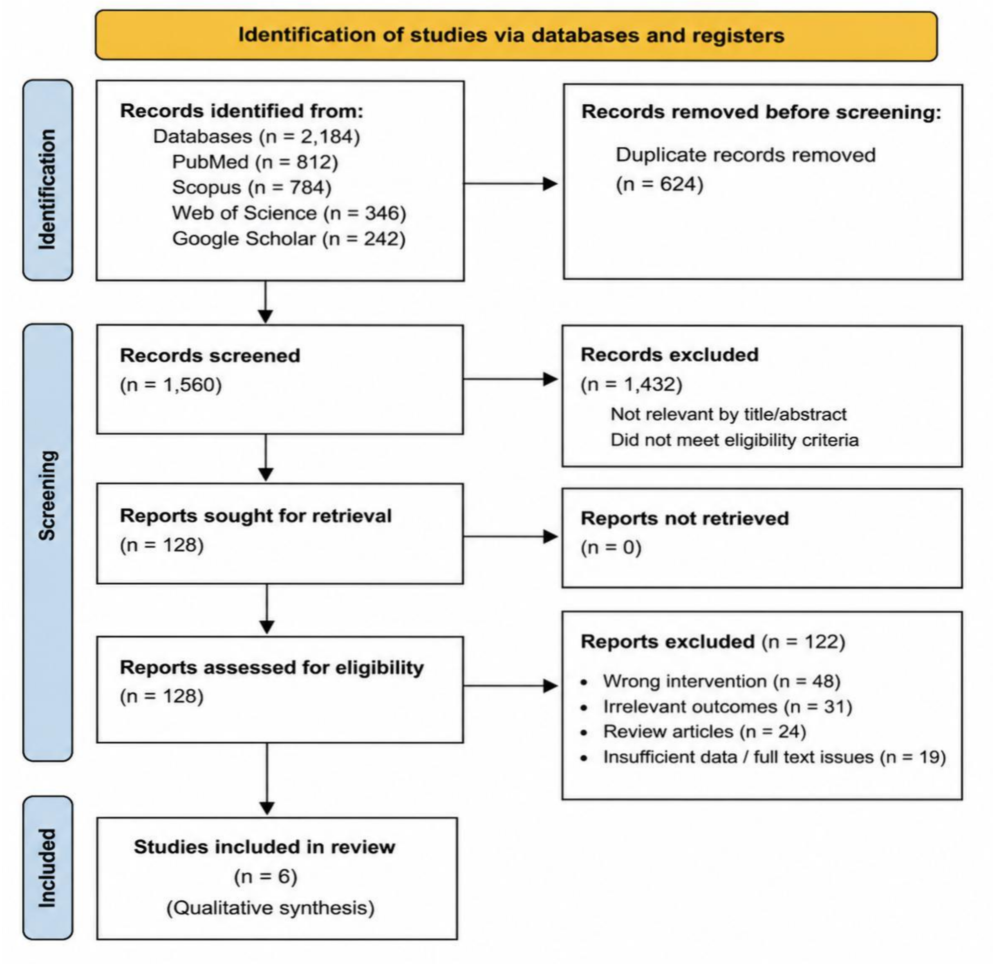
Figure 6
PRISMA Flow Diagram of Study Selection Process



The characteristics of the included studies are summarized in Table 1. The six included studies were published between 2014 and 2023 and were conducted across India, Brazil, and Spain. Among these, two were randomized clinical trials, while four were ex vivo experimental studies. Sample sizes ranged from 10 to 80 participants or extracted teeth. The included studies compared various irrigation activation techniques, including passive ultrasonic irrigation, sonic irrigation, manual dynamic agitation, EasyClean activation, and conventional syringe irrigation. The primary outcomes assessed across studies included smear layer removal, debris elimination, bacterial reduction, and postoperative pain.

Table 1 Characteristics of Included Studies

Author(s), Year	Country	Study Design	Sample Size	Intervention/Comparison	Outcome Measures	Key Findings
Khaord and	India	Ex vivo comparative study	40 extracted	Passive ultrasonic irrigation, sonic irrigation, manual	Smear layer removal (SEM)	Sonic irrigation demonstrate

Amin (2015)			molar canals	dynamic agitation, and conventional irrigation		d the most effective smear layer removal among the tested groups.
Mozo et al. (2014)	Spain	Ex vivo study	40 extracted single-rooted teeth	Conventional irrigation versus passive ultrasonic irrigation	Smear layer removal and dentinal tubule opening	Passive ultrasonic irrigation significantly improved canal cleanliness, particularly in the apical third.
Kato et al. (2016)	Brazil	Ex vivo comparative study	10 mandibular mola	Passive ultrasonic irrigation versus EasyClean activation	Debris removal (Environmental SEM	EasyClean Demonstrated superior debris removal in the apical region compared with passive ultrasonic irrigation.
Orozco et al. (2020)	Brazil	Randomized clinical trial	20 patients	Passive ultrasonic activation versus conventional needle irrigation	Bacterial reduction	Passive ultrasonic activation resulted in a greater reduction of cultivable intracanal bacteria.
Palanisamy et al. (2023)	India	Randomized controlled trial	80 patients	Ultrasonic irrigation versus side-vented needle irrigation	Bacterial load and postoperative pain	Ultrasonic irrigation showed superior bacterial reduction and reduced postoperative pain.

Frontier in Medical & Health Research
ISSN: (e) 3007-1607 (p) 3007-1593

Machado et al. (2021)	Brazil	Ex vivo comparative study	45 premolars	Conventional application, passive ultrasonic irrigation, EasyClean, and XP-Endo Finisher	Smear layer remov (SEM)	None of the techniques completely removed the smear layer; differences were observed across canal thirds.

Smear Layer Removal

Among the six included studies, four studies evaluated the effectiveness of different irrigation activation techniques in smear layer or debris removal. Khaord and Amin (2015) compared passive ultrasonic irrigation, sonic irrigation, manual dynamic agitation, and conventional syringe irrigation and reported that sonic irrigation demonstrated superior smear layer removal, particularly in the apical third of the root canal. Similarly, Mozo et al. (2014) found that passive ultrasonic irrigation significantly improved dentinal tubule opening and debris elimination compared with conventional syringe irrigation, especially in the apical region. Kato et al. (2016) compared passive ultrasonic irrigation with EasyClean activation and observed that EasyClean showed superior debris removal in the apical regions of the canal. In contrast, Machado et al. (2021) reported that although all tested activation methods improved canal cleanliness, none of the techniques completely removed the smear layer in all root canal thirds. The comparative outcomes related to smear layer removal across the included studies are summarized in Table 2.

Table 2 Comparative Outcomes of Smear Layer Removal

Study	Activation Technique	Assessment Method	Apical Third	Middle Third	Coronal Third	Overall Outcome
Khaord and Amin (2015)	Sonic irrigation, passive ultrasonic irrigation, manual dynamic agitation, conventional irrigation	Scanning electron microscopy (SEM)	Sonic showed best cleaning	Sonic showed effective cleaning	All groups showed acceptable cleaning	Sonic irrigation demonstrated superior smear layer removal.
Mozo et al. (2014)	Passive ultrasonic irrigation vs conventional irrigation	Scanning electron microscopy (SEM)	PUI significantly better	PUI better	Similar outcomes	PUI improved dentinal tubule opening and smear layer removal.
Kato et al. (2016)	Passive ultrasonic	Environmental SEM	EasyClean superior	Comparable outcomes	Comparable outcomes	EasyClean showed better apical

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	irrigation vs EasyClean					debris removal.
Machado et al. (2021)	Conventional application, PUI, EasyClean, XP-Endo Finisher	Scanning electron microscopy (SEM)	Moderate cleaning in all groups	Improved cleaning	Best cleaning observed	No technique completely removed smear layer.

Overall, the evidence suggests that activated irrigation systems consistently outperformed conventional syringe irrigation in smear layer and debris removal. Among the evaluated techniques, sonic and ultrasonic activation demonstrated the most favorable cleaning outcomes, particularly in the apical third of the root canal. However, none of the included studies reported complete smear layer elimination across all canal regions, indicating that anatomical complexity remains a major clinical challenge.

Bacterial Reduction

Among the included studies, two randomized clinical trials evaluated the antibacterial effectiveness of irrigation activation techniques during root canal treatment. Orozco et al. (2020) compared passive ultrasonic activation with conventional needle irrigation in patients with primary endodontic infection and found that ultrasonic activation resulted in significantly greater reduction in cultivable bacterial counts following chemomechanical preparation. Similarly, Palanisamy et al. (2023) compared passive ultrasonic irrigation with side-vented needle irrigation in patients undergoing root canal therapy and reported that the ultrasonic group showed a higher proportion of bacteria-free samples, along with lower postoperative pain scores. Overall, the available clinical evidence suggests that ultrasonic activation may provide superior antibacterial efficacy compared with conventional needle-based irrigation techniques. The comparative antibacterial outcomes of the included studies are summarized in Table 3.

Table 3 Comparative Outcomes of Bacterial Reduction

Study	**Technique Compared**	**Pre-treatment Status**	**Post-treatment Outcome**	**Additional Clinical Findings**	**Overall Outcome**
Orozco et al. (2020)	Passive ultrasonic activation vs conventional needle irrigation	Primary endodontic infection with cultivable bacteria	Significant bacterial reduction in both groups	Ultrasonic group showed greater bacterial elimination	Ultrasonic activation demonstrated superior antibacterial efficacy.
Palanisamy et al. (2023)	Ultrasonic irrigation vs side-vented needle irrigation	Detectable bacterial contamination	Higher number of bacteria-free samples in ultrasonic group	Reduced postoperative pain in ultrasonic group	Ultrasonic irrigation showed better clinical and antibacterial outcomes.

Collectively, the available clinical evidence indicates that passive ultrasonic activation provides superior antibacterial efficacy compared with conventional needle-based irrigation

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Frontier in Medical & Health Research

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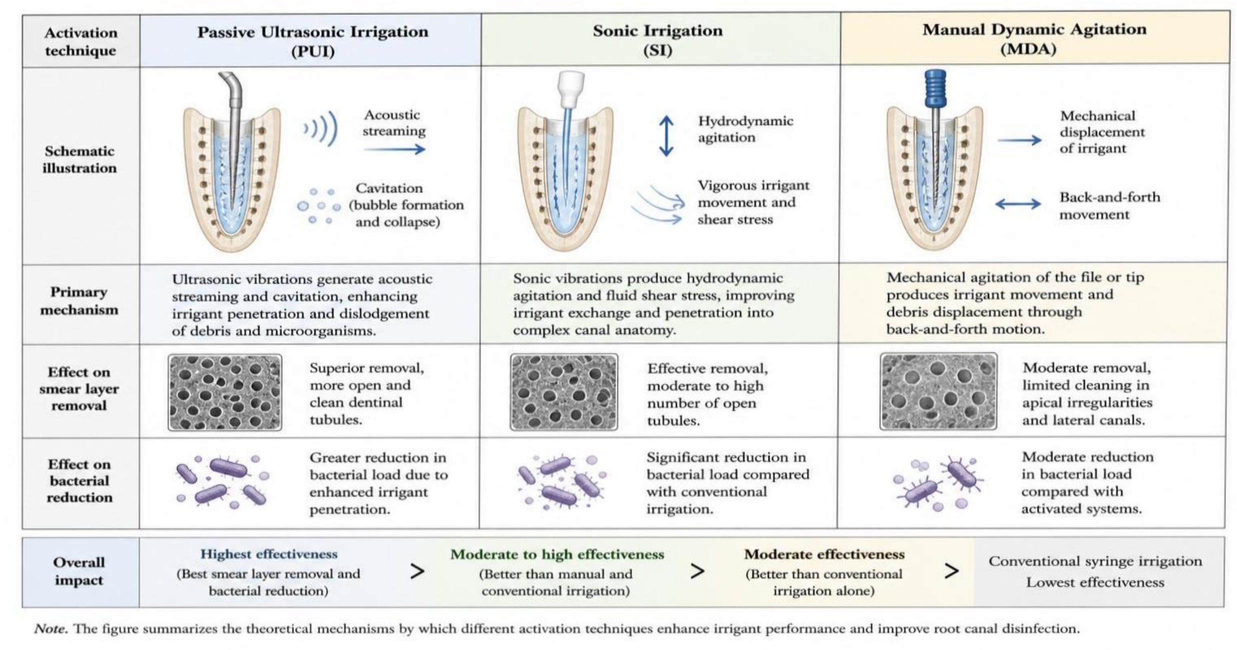
techniques. Enhanced irrigant penetration and improved fluid exchange within the root canal system may explain the greater bacterial reduction observed in ultrasonic groups.

Discussion

The present systematic review evaluated the comparative effectiveness of different irrigation activation techniques, including passive ultrasonic irrigation, sonic irrigation, manual dynamic agitation, and conventional syringe irrigation, in reducing intracanal bacterial load and removing the smear layer during endodontic treatment. Based on the six included studies, the findings consistently suggest that activated irrigation systems, particularly ultrasonic and sonic activation techniques, demonstrated superior cleaning efficacy and antibacterial performance compared with conventional irrigation methods [13–18]. The overall evidence indicates that irrigation activation plays a critical role in improving root canal disinfection and enhancing canal wall cleanliness, which are essential for long-term endodontic success. The proposed mechanisms underlying the enhanced performance of irrigation activation techniques are illustrated in Figure 7.

Figure 7 Proposed mechanisms of irrigation activation techniques and their impact on root canal cleanliness



One of the major findings of this review was the improved smear layer removal associated with activated irrigation techniques. Khaord and Amin [13] compared passive ultrasonic irrigation, sonic irrigation, manual dynamic agitation, and conventional syringe irrigation and found that sonic irrigation demonstrated the most effective smear layer removal, particularly in the apical third of the root canal. This may be explained by the hydrodynamic movement created by sonic activation, which improves irrigant penetration into anatomically complex regions. Similarly, Mozo et al. [14] reported that passive ultrasonic irrigation significantly improved smear layer removal and dentinal tubule opening compared with conventional syringe irrigation. Ultrasonic activation creates acoustic streaming and cavitation effects, which enhance debris displacement and improve the contact of irrigants with dentinal surfaces. These findings support the growing evidence that activated irrigation systems

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are more effective in removing the smear layer than conventional irrigation alone.

Further supporting these observations, Kato et al. [15] demonstrated that EasyClean activation achieved superior debris removal in the apical region compared with passive ultrasonic irrigation. Although EasyClean was not one of the primary interventions of this review, its inclusion highlights the importance of mechanical activation in enhancing root canal cleanliness. Similarly, Machado et al. [16] found that although all activation systems improved smear layer removal, none of the tested techniques completely eliminated the smear layer from all root canal thirds. This suggests that while activation improves cleaning efficacy, complete debridement of complex root canal systems remains challenging. Variations in root canal anatomy, preparation size, irrigant volume, and activation time may contribute to these differences.

In addition to smear layer removal, bacterial reduction was another critical outcome evaluated in this review. Orozco et al. [17] compared passive ultrasonic activation with conventional needle irrigation in patients with primary endodontic infections and reported significantly greater bacterial reduction in the ultrasonic group. The enhanced antibacterial effect of ultrasonic activation may be attributed to improved irrigant exchange and deeper penetration of antimicrobial solutions into dentinal tubules. Similarly, Palanisamy et al. [18] found that passive ultrasonic irrigation resulted in a higher proportion of bacteria-free samples and reduced postoperative pain compared with side-vented needle irrigation. These findings suggest that activated irrigation techniques not only improve microbiological disinfection but may also contribute to better postoperative outcomes.

The risk of bias and quality assessment demonstrated that the included randomized clinical trials showed an overall low risk of bias, while most ex vivo studies demonstrated high methodological quality. This strengthens the reliability of the findings of this review. However, certain limitations should be considered when interpreting these results. First, only six studies met the eligibility criteria, which may limit the generalizability of the findings. Second, most included studies were ex vivo laboratory investigations, which may not fully replicate clinical conditions. Third, methodological heterogeneity among studies, including differences in irrigant concentration, activation protocols, instrumentation techniques, and outcome assessment methods, may have influenced the observed outcomes.

Despite these limitations, the present review provides clinically relevant evidence supporting the use of irrigation activation techniques during root canal treatment. Ultrasonic and sonic irrigation systems appear to offer superior smear layer removal and bacterial reduction compared with conventional syringe irrigation. Future large-scale randomized clinical trials with standardized protocols are recommended to further establish the clinical superiority of these activation systems and optimize irrigation protocols in endodontic practice.

Limitations

Several limitations of this systematic review should be acknowledged. First, only six studies met the predefined eligibility criteria, which may limit the overall generalizability of the findings. Second, the majority of the included studies were ex vivo experimental studies rather than clinical trials, which may not fully replicate the complexity of in vivo root canal conditions. Third, substantial methodological heterogeneity was observed among the included studies in terms of sample characteristics, irrigant concentration, activation protocols, instrumentation systems, and outcome assessment methods. Additionally, variations in evaluation techniques, including scanning electron microscopy and microbiological culture analysis, may have influenced the comparability of results across studies. Therefore, the findings of this review should be interpreted with consideration of these methodological differences.

Conclusion

Within the limitations of this systematic review, irrigation activation techniques, particularly passive ultrasonic irrigation and sonic irrigation, demonstrated superior effectiveness in smear layer removal and bacterial reduction compared with

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conventional syringe irrigation. Activated irrigation systems consistently improved root canal cleanliness, especially in the apical third, and showed enhanced antimicrobial performance in clinical settings. These findings suggest that incorporating irrigation activation techniques into routine endodontic practice may improve disinfection efficiency and potentially enhance treatment outcomes. However, further well-designed randomized clinical trials with standardized protocols are required to establish stronger clinical evidence and optimize irrigation strategies in endodontic therapy.

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