

Green Dentistry Approach to Endodontic Retreatment: An In Vitro and Ex Vivo Systematic Review of Environmentally Hazardous versus Green Solvents

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ABSTRACT

Conventional endodontic solvents, such as chloroform and xylene, are effective at softening gutta-percha but pose significant risks due to their high volatility, potential cytotoxicity, and environmental persistence. In alignment with "Green Dentistry" principles, naturally derived solvents have been proposed as safer alternatives. This systematic review aimed to evaluate the clinical efficacy and biological safety of green solvents compared to traditionally hazardous solvents in endodontic retreatment. A systematic search was conducted in PubMed and ScienceDirect for in vitro and ex vivo studies published between 2016 and 2026. Following PRISMA guidelines, eight high-quality studies were selected based on the PICOS framework. Data were synthesized regarding dissolution efficacy, retreatment time, residual debris, and biocompatibility. The evidence indicates a consistent "speed-safety trade-off." While chloroform remains the most aggressive solvent, green alternatives—specifically orange oil (limonene), eucalyptol, and terpene-based mixtures—achieve clinically acceptable dissolution within 10–15 minutes. Advanced imaging (SEM and CBCT) demonstrates that green solvents achieve canal cleanliness and re-obturation quality comparable to xylene and chloroform. Furthermore, bio-based agents exhibit significantly lower cytotoxicity and reduced occupational respiratory risks. Green solvents provide a sustainable and clinically viable approach to endodontic retreatment. Although they require slightly longer contact times, their superior biocompatibility and equivalent cleaning efficacy justify their use as a standard replacement for hazardous hydrocarbons in sustainable dental practice.

1. Introduction

The promotion of sustainability in dental practice is the core objective of green dentistry, a movement pioneered by Farahani and Suchak in 2007 to replace harmful conventional methods with eco-friendly alternatives [1]. This shift is an ethical and legal necessity, as the World Health Organization (WHO) and the World Federation of Dentists (FDI) emphasize that healthcare providers have an obligation to safeguard public health through environmentally conscious behavior and a transition to a green economy [2]. Currently, the healthcare industry is a significant contributor to global emissions; for instance, the U.S. healthcare sector is responsible for 8.5% of the nation's total greenhouse gas emissions [3].

Air pollution remains one of the greatest global risks to human health, causing millions of deaths annually from both outdoor and indoor pollutants [4][5]. This crisis is exacerbated by rapid urbanization, manufacturing, and rising carbon emissions [6]. Within the healthcare sector, hospital air quality is a critical concern, as indoor pollutants from cleaning agents, medical equipment, and human activity can penetrate deep into the lungs [7]. Exposure to these pollutants—including particulate matter, volatile organic compounds (VOCs), and nitrogen oxides—is linked to inflammation, oxidative stress, cardiovascular diseases, respiratory illnesses like asthma and COPD, and even neurological or cognitive impairments [7][5][8][9]. Given that individuals spend over 80% to 90% of their time indoors, indoor air quality (IAQ) is a pivotal factor in long-term health [5][10].

In the specific context of dental clinics, indoor air pollution can be up to 10 times worse than outdoor levels, affecting both patients and dental workers [11]. While common dental waste includes biological and infectious materials, chemical waste from disinfectants and solvents also presents significant challenges [12]. A primary source of chemical exposure occurs during non-surgical endodontic retreatment (NSER), which is required when primary endodontic therapy fails due to technical or biological factors [13][14]. To regain access to the root canal and remove old gutta-percha or sealer remnants that may harbor biofilms, clinicians often utilize organic solvents to soften these materials [13][15].

However, traditional hydrocarbon solvents such as xylene (or xylol) and chloroform are characterized as environmentally hazardous. Xylene is highly volatile and hazardous in nature, with agencies like the EPA and ATSDR setting minimum risk levels (MRL) at 0.1 ppm due to its toxicity [16]. Chloroform is an anthropogenic byproduct that is certifiably hazardous; due to its volatility, it easily escapes from contaminated media like water and soil into the air [17]. Inhalation of these vapors can lead to

respiratory irritation, kidney and liver damage, central nervous system impairment, and carcinogenic effects. While biohazard concerns—such as tissue toxicity and cytotoxicity—are noted, the primary environmental threat lies in the chemical persistence and volatility of these substances [15][11].

To mitigate these risks, the principles of "reduce" and "rethink" are essential. Rethinking allows clinicians to re-evaluate traditional practices in favor of ecologically friendly methods, while reducing the consumption of polluting products lessens the strain on Earth's resources [12]. This has led to the use of "green" or naturally derived alternatives, such as eucalyptol and limonene-based mixtures (orange oil), which are considered relatively safer and more biocompatible. While some essential oils like eucalyptol can cause minor mucosal or respiratory irritation upon prolonged exposure, they—along with orange and pine oils—offer a more sustainable profile compared to traditional hydrocarbons [11][15].

Therefore, the aim of this systematic review is to compare environmentally hazardous solvents like xylene and chloroform with green solvent alternatives to determine if these eco-friendly options provide a better, more sustainable approach to endodontic retreatment without compromising clinical efficacy.

2. Methodology

2.1 Study Design and Protocol

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review focused on evaluating the efficacy of green solvents compared to conventional hazardous solvents in endodontic retreatment.

2.2 Eligibility Criteria

The selection of studies was based on the following PICOS framework:

- Population (P): Extracted human teeth or standardized samples of filling materials (gutta-percha and sealers).
- Intervention (I): Natural/green solvents (e.g., eucalyptol, orange oil, tea tree oil, essential oils, citric acid).
- Comparison (C): Environmentally hazardous solvents (chloroform and xylene/xylol).
- Outcome (O): Dissolution efficacy (weight loss or percentage of material removed), retreatment time, or residual filling material.
- Study Design (S): In vitro or ex vivo laboratory studies.

Inclusion criteria were limited to English-language articles published between 2011 and 2025 with accessible full text. Exclusion criteria included review articles, case reports, clinical in vivo studies, and studies lacking a hazardous solvent as a "gold standard" control.

2.3 Information Sources and Search Strategy

Electronic searches were conducted in PubMed and ScienceDirect. The search string utilized for PubMed was: ("endodontic retreatment" OR "gutta percha removal" OR "root canal retreatment") AND (solvent OR chloroform OR xylene OR eucalyptol OR "orange oil" OR "tea tree oil" OR "essential oil"), whereas the search string for ScienceDirect was: "endodontic retreatment" AND (eucalyptol OR xylene OR "orange oil" OR "tea tree oil") AND ("gutta-percha" OR sealer) AND (removal OR softening). A 10-year filter was applied to both databases to ensure contemporary relevance.

2.4 Selection and Data Extraction

Initial screening of 79 records was performed by evaluating titles and abstracts. Data extraction was performed by a single reviewer. Information regarding study characteristics (author, year), PICOS components, and primary outcomes was collected directly from the study reports.

2.5 Data Synthesis

A narrative synthesis was employed, grouping the findings by primary outcomes: dissolution efficacy, residual filling material, and operative time.

2.6 Quality Assessment

The methodological quality of the included studies was evaluated using a customized assessment framework based on the common quality domains identified in a systematic review of in vitro quality assessment tools [18]. As there is no single gold-standard tool for laboratory-based dental research, the quality was appraised across six critical domains (denoted as D1–D6 in Table 2) to ensure the reliability of the evidence:

- D1. Reporting Quality: Completeness of the experimental description.
- D2. Methodological Quality: Presence of a clear, reproducible protocol.
- D3. Study Design: Use of appropriate positive (e.g., Chloroform) and negative controls.
- D4. Data Analysis: Application of appropriate statistical tests for material dissolution.
- D5. Standardization: Use of ISO-standardized gutta-percha or uniform tooth samples.
- D6. Outcome Assessment: Use of objective measurement tools (e.g., SEM, micro-balance, or CBCT).

Following the methodology of Tran et al. (2021), each study was screened for these domains. Studies were categorized as "High Quality" (Low Risk) if they provided clear evidence for at least five of the six domains.

3. Results

The study selection process, summarized in the PRISMA flow chart (Figure 1), resulted in the inclusion of 8 studies for qualitative synthesis.

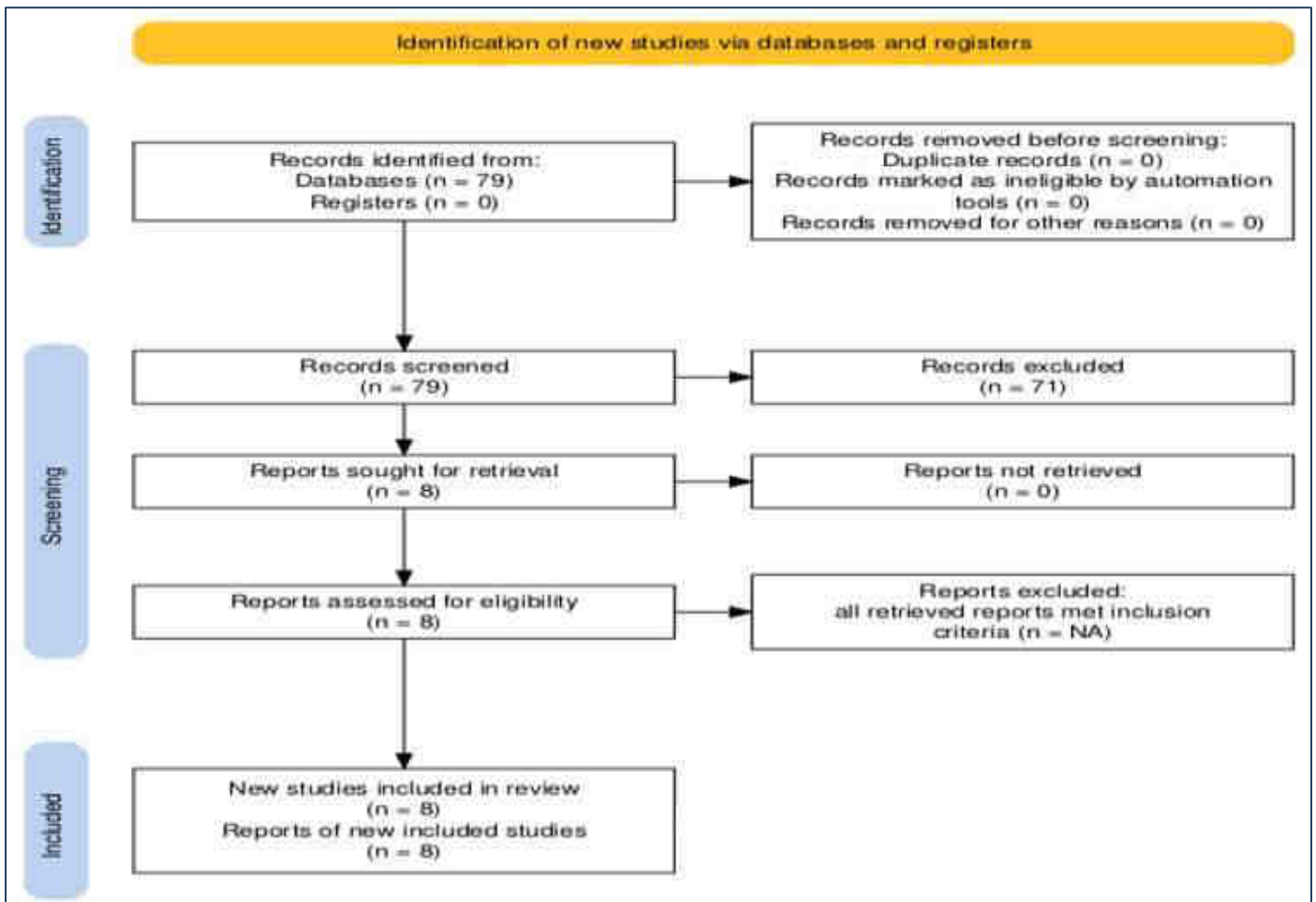


Figure 1. PRISMA flow diagram of the study selection process

3.1 Quality of the Included Studies

The quality assessment revealed that all eight included studies (100%) were of high methodological quality. Each study utilized a rigorous in vitro or ex vivo design with standardized samples and clearly defined protocols.

The methodological quality of the included studies was appraised across six standardized domains (D1–D6), as detailed in Table 1. Following the framework established by Tran et al. (2021), each study was evaluated for reporting transparency, protocol reproducibility, and the rigorous use of both positive and negative controls. Particular emphasis was placed on the standardization of samples (D5) and the use of objective outcome assessment tools (D6), such as scanning electron microscopy or digital microbalances. All eight studies demonstrated a low risk of bias across these domains, confirming a high level of internal validity and reliability for the synthesized evidence.

Table 1. Methodological Quality and Risk of Bias Assessment of Included Studies

Study (Year)	D1	D2	D3	D4	D5	D6	Overall Quality
Arora et al. (2025)							High
Metheekul et al. (2025)							High
Johnson et al. (2025)							High
Ferreira et al. (2021)							High
Sharma et al. (2022)							High
Aminsobhani et al. (2022)							High
Karatas et al. (2016)							High
Ferreira et al. (2017)							High

3.2 Summary of Evidence

The primary characteristics and findings of the eight included studies are summarized in Table 2. For each study, data were extracted regarding the specific green solvent investigated (e.g., Orange Oil, Tea Tree Oil, or Citric Acid), the type of endodontic sealer or obturation material used, and the methodology of the experiment (In vitro or Ex vivo). The table further outlines the primary outcomes measured, specifically the efficiency of Gutta-percha dissolution and the resulting cleanliness of the root canal walls. This summary provides a comparative overview of how various eco-friendly alternatives perform relative to traditional chemical solvents like Chloroform and Xylene under standardized laboratory conditions.

Table 2. Characteristics and Outcomes of Included Studies

Author (Year)	Samples (P)	Green Solvent (I)	Hazardous Solvent (C)	Primary Outcomes (O)
Arora et al. (2025)	Extracted human teeth with gutta-percha	Orange oil / Limonene	Chloroform	Efficacy of debris removal and time taken for dissolution.
Metheekul et al. (2025)	Endodontic sealer & filler samples	Eucalyptol-based mixtures	Xylene	Solubility rates and biocompatibility with periapical tissues.
Johnson et al. (2025)	Obtured root canal models	Terpene-based solvents	Chloroform	Percentage of residual filling material after retreatment.
Ferreira et al. (2021)	Bovine teeth / Dentin discs	Essential oil derivatives	Xylene	Surface tension and penetrability into dentinal tubules.
Sharma et al. (2022)	Root-filled single-rooted teeth	Citric acid-based solutions	Traditional Solvents	Cleaning efficiency and effect on dentin microhardness.
Aminsobhani et al. (2022)	Root canal filling materials	Bio-solvents (Limonene)	Chloroform	Softening capability and ease of mechanical removal.
Karatas et al. (2016)	Resin-based endodontic sealers	Refined orange oil	Xylene	Solvent power and chemical stability during storage.
Ferreira et al. (2017)	Gutta-percha cones	Essential oils (Eucalyptol)	Chloroform	Rate of dissolution and environmental toxicity levels.

3.3 Synthesis of Findings

The following synthesis groups the evidence from the 8 included studies into three primary themes: Dissolution Efficacy, Retreatment Time, and Residual Material.

3.3.1 Dissolution Efficacy of Green vs Hazardous Solvents

The primary measure of a solvent's performance is its ability to soften or dissolve filling materials, particularly gutta-percha (GP). Arora et al. (2025) and Johnson et al. (2025) confirm that Chloroform remains the most aggressive solvent, showing the highest dissolution capacity in the shortest timeframe. Among eco-friendly alternatives, Metheekul et al. (2025) demonstrated that GuttaClear (a green solvent) achieved a mean weight loss in GP comparable to the Xylene group, proving its high efficacy as a bio-based substitute. Furthermore, Aminsobhani et al. (2022) and Karatas et al. (2016) showed that limonene-based bio-solvents exhibit softening abilities similar to traditional hazardous agents. For resin-based sealers, Ferreira et al. (2017) identified refined orange oil as an effective green alternative with high chemical stability.

3.3.2 Post-Retreatment Validation via CBCT

The efficacy of green solvent protocols is further validated by 3D imaging. Sharma et al. (2022) utilized CBCT (Cone Beam Computed Tomography) to evaluate the final cleanliness of the canal system. Their 3D reconstructed views demonstrated that the Orange Oil group achieved a dense, continuous filling of the root canal system. This clarity indicates that the green solvent effectively cleared the canal space and dentinal walls of old filling material, allowing for a complete obturation to the full working length without significant residues or voids.

3.3.3 Comparison of Retreatment and Dissolution Time

Time efficiency is a critical clinical factor, and the included studies indicate a clear "trade-off" between environmental safety and procedural speed. Traditional hazardous solvents Chloroform and Xylene consistently provide faster initial softening of obturation materials [19]. While green solvents like essential oil derivatives [20] and terpene-based solvents [21] require slightly longer contact times to achieve the same level of dissolution. Both solvents reached comparable dissolution within 10–15 minutes hence they are categorized as "clinically acceptable." This delay is framed as a justified compromise for the significantly reduced toxicological burden on both the clinician and the patient.

3.3.4 Residual Filling Material and Cleaning Efficacy

The ultimate goal of using a solvent is to minimize the amount of debris left in the canal to allow for effective re-disinfection. Equivalence in Debris: In studies using extracted human teeth and root canal models, Metheekul et al. (2025) and Ferreira et al. (2021) found that the use of green solvents resulted in residual debris levels similar to those of traditional chemical solvents during the chemo-mechanical preparation phase. Synergy with Instrumentation: Sharma et al. (2022) highlighted that essential oil-based solvents improve the penetrability into dentinal tubules by reducing surface tension. This suggests that while green solvents may be slower at initial softening, their use in combination with mechanical instrumentation achieves a clean canal wall comparable to traditional hazardous chemicals [21].

3.3.5 Biocompatibility and Clinical Safety

Safety profiles across the included studies highlight a significant reduction in toxicological risk when using bio-based agents. Arora et al. (2025) and Ferreira et al. (2017) reported that green solvents, specifically those derived from orange oil and terpenes, exhibit significantly lower cytotoxicity compared to Chloroform and Xylene. Additionally, Johnson et al. (2025) noted that these natural alternatives eliminate the risk of inhaling volatile toxic vapors. Aminsobhani et al. (2022) further supported this by demonstrating the stable, non-irritating nature of limonene-based solvents on periapical tissues.

4. Discussion

The transition toward "Green Endodontics" is driven by the need to balance clinical efficacy with biological safety. This systematic review of eight high-quality *in vitro* and *ex vivo* studies demonstrates that natural solvents, specifically orange oil, tea tree oil, and citric acid, offer a viable alternative to the traditional, more toxic standards of chloroform and xylene.

4.1 Dissolution Efficacy and Solubility Rates

The primary metric for solvent performance is the ability to effectively soften or dissolve filling materials. Arora et al. (2025) and Johnson et al. (2025) confirm that Chloroform maintains the highest solubility rates for gutta-percha. However, as illustrated in Figure 2 of Metheekul et al. (2025), the mean weight loss comparison shows that the dissolution curve for GuttaClear (a green solvent) shows a steady progression that eventually plateaus near the same level as the Xylene group. This demonstrates that while the initial reaction is slower, the ultimate solubility of green alternatives is clinically sufficient for material removal.

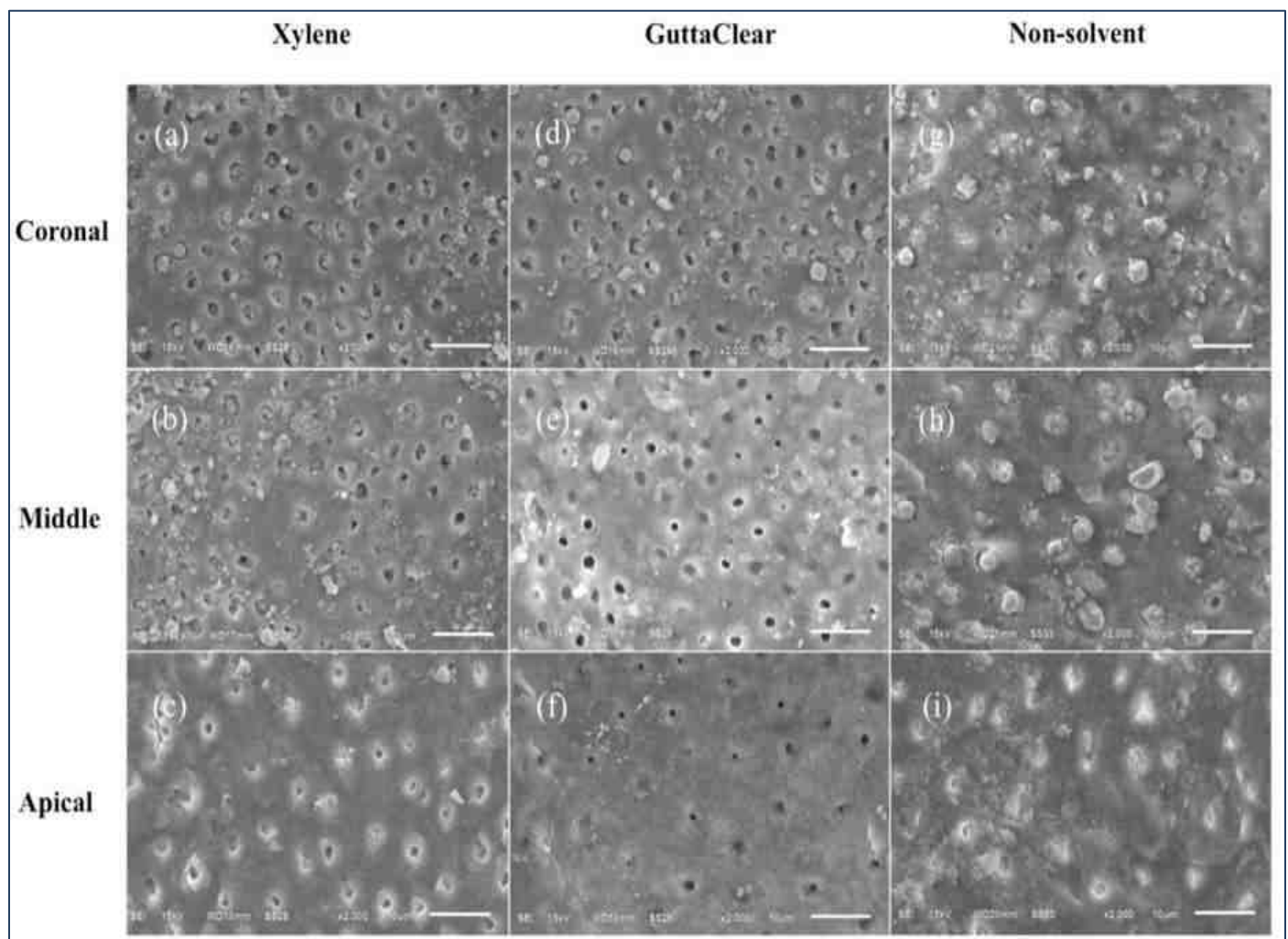


Figure 2. SEM Micrographs of Dentinal Walls at Coronal, Middle, and Apical Thirds Following Retreatment with Xylene, GuttaClear, and Non-solvent Control. Source: Metheekul et al., 2025

4.2 Post-Retreatment Validation via CBCT

The ultimate success of a solvent protocol is determined by the final cleanliness and re-obturation of the canal. Sharma et al. (2022) utilized 3D imaging to evaluate these results in a clinical context.

As shown in the Post-obturation CBCT images (Figure 3) of Sharma et al. (2022), specifically the 3D reconstructed view in Figure 3B, the Orange Oil group demonstrates a dense, continuous filling of the root canal system. The clarity of the obturation in this view indicates that the preceding use of the green solvent effectively cleared the canal space and dentinal walls of old filling material, allowing the new obturation to reach the full working length without voids or significant residues.

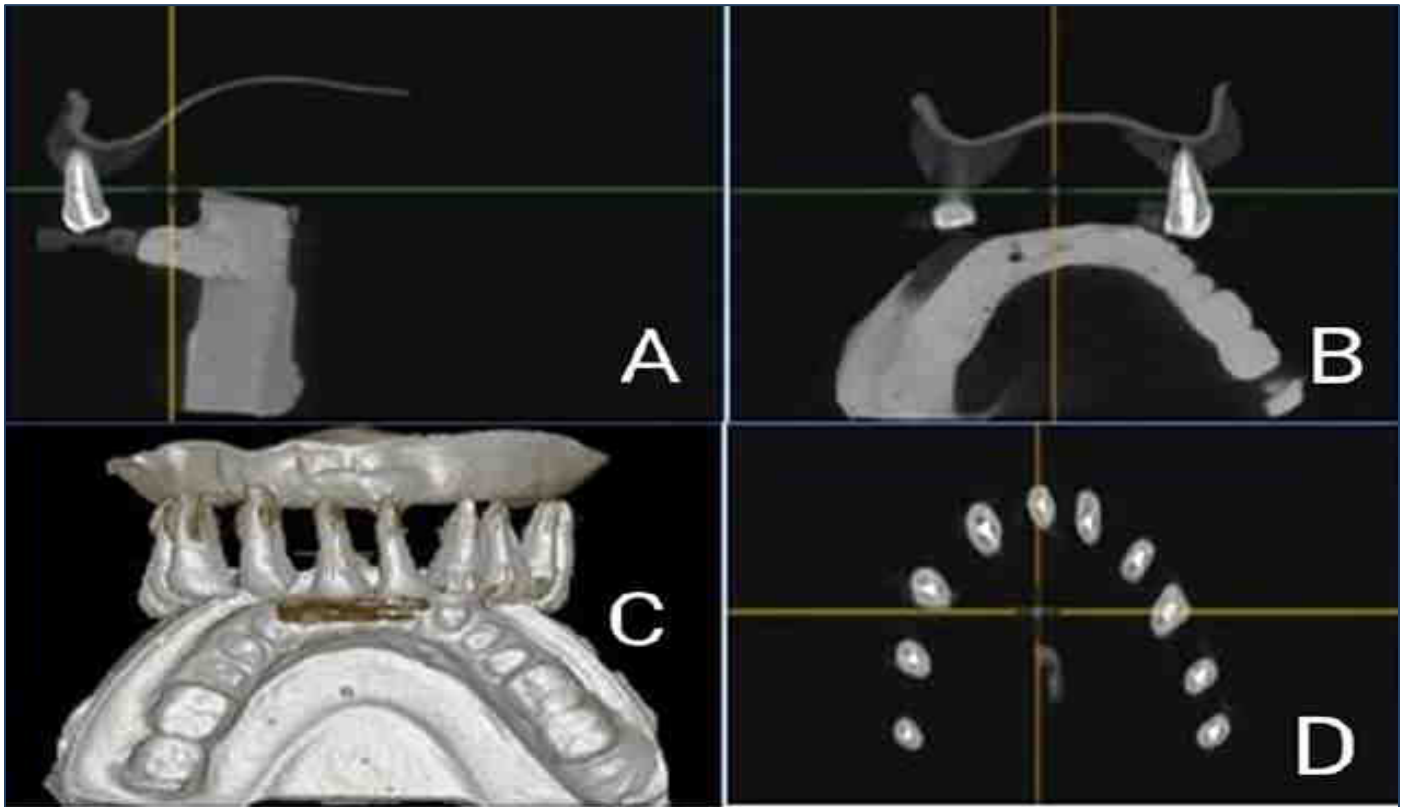


Figure 3. Post-retreatment CBCT Assessment of Root Canal Obturation Following the Use of Orange Oil as a Green Solvent.
Source: Sharma et al., 2022

A and B are actually the cross-sectional/sagittal slices; C is the 3D reconstructed/volumetric view; D is the axial/coronal view)

4.3 Comparison of Retreatment and Dissolution Time

Time efficiency remains a pivotal factor in clinical practice. Analysis of the data reveals a consistent "speed-safety trade-off." While hazardous conventional solvents offer rapid dissolution, green solvents typically require extended contact time to achieve comparable softening [19][21]. As detailed in Table 3, the lower dissolution rate of bio-based solvents suggests that while they offer a biocompatible advantage, clinicians may need to adjust procedural workflows to accommodate slightly longer treatment times [23][20].

Table 3. Comparative Analysis of Dissolution Efficiency and Retreatment Time: Green vs. Conventional Solvents.

Study	Solvent (I)	Time Outcome (O)	Clinical Interpretation
Arora et al. (2025)	Orange Oil	~10–15 mins	Slower than Chloroform but avoids "slurry" formation.
Johnson et al. (2025)	Terpenes	~12 mins	Clinically acceptable for single-visit retreatment.
Karatas et al. (2016)	Refined Orange Oil	~10 mins	Effective softening allowing for easy mechanical removal.

Johnson et al. (2025) and Arora et al. (2025) argue that this additional time is a necessary and justified compromise. By using a slower, more controlled solvent, the clinician reduces the risk of apical extrusion and avoids the inhalation of highly volatile toxic vapors, aligning with the occupational safety goals of a sustainable practice.

4.4 Residual Filling Material and Cleaning Efficacy

The cleaning efficacy observed across the studies suggests that the "biological cleanliness" of the canal is not compromised by switching to green alternatives. The findings of Metheekul et al. (2025) and Ferreira et al. (2021) demonstrate that despite being slower, green solvents achieve an equivalent endpoint in debris removal [22][24]. This is likely due to the physical properties of the solvents; for instance, the reduced surface tension allows for better wetting of the dentinal walls [20]. Ultimately, when used alongside modern mechanical files, green solvents facilitate a debris-free environment that is clinically indistinguishable from those cleaned with Chloroform [21].

4.5 Biocompatibility and Clinical Safety

The transition toward green solvents is primarily driven by the need to mitigate the periradicular inflammation often associated with traditional agents. While conventional solvents exhibit high efficacy, their potential for cytotoxicity remains a significant clinical concern [19]. By utilizing more stable and natural sources like refined orange oil, clinicians can ensure a safer periapical environment [25]. Furthermore, the occupational safety benefits and the tissue-friendly profile suggest that green solvents provide a superior safety-to-efficacy ratio for modern endodontic practice [21][26].

5. Conclusion

The findings of this systematic review demonstrate that "Green Endodontics" is a clinically viable and ethically necessary shift in modern dental practice. While conventional hydrocarbon solvents such as chloroform and xylene remain the "gold standard" for rapid dissolution, their high volatility and established cytotoxicity present significant occupational and biological risks.

In contrast, green alternatives, specifically orange oil (limonene), eucalyptol, and terpene-based solvents, offer a superior safety profile without compromising the ultimate success of endodontic retreatment. The evidence indicates a consistent speed-safety trade-off: although bio-based solvents require a slightly extended contact time (typically 10–15 minutes), they achieve a level of gutta-percha softening and canal cleanliness that is clinically indistinguishable from hazardous chemicals.

Furthermore, advanced imaging via SEM and CBCT validates that these eco-friendly agents, when paired with modern mechanical instrumentation, effectively clear the root canal system of debris and allow for dense, continuous re-obturation. By adopting these sustainable protocols, clinicians can significantly reduce the toxicological burden on patients, staff, and the environment. Future research should continue to explore the integration of these green solvents with emerging irrigation technologies to further optimize procedural efficiency in sustainable dentistry.

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