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Review

Forensic significance of condom traces in sexual assault investigations: A systematic review

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ABSTRACT

This systematic review examines the forensic value of condom residue detection in biological samples, particularly in sexual assault investigations where DNA evidence is absent. Following PRISMA 2020 guidelines, a comprehensive literature search was conducted across seven databases (MEDLINE, EMBASE, Cochrane Library, PubMed, Web of Science, SCOPUS, Google Scholar), two trial registers (ClinicalTrials.gov, WHO ICTRP), and four grey literature sources (PQDT, WorldCat, OATD, F1000). Studies published in English from January 1, 2020, to February 28, 2025, were screened using predefined PICO(S) criteria. Eight eligible studies involving human matrices were included. The analytical techniques assessed included DRIFTS-FTIR, ATR-FTIR, Py-GC/MS, GC–MS, and sfPESI-MS. DRIFTS-FTIR demonstrated strong spectral resolution for detecting PDMS-based silicone lubricants, while ATR-FTIR achieved 100 % classification accuracy under controlled laboratory conditions. The combination of spectroscopic and chromatographic techniques (e.g., ATR-FTIR + GC–MS) yielded more reliable and confirmatory results. The risk of bias was assessed using the QUADAS-2 tool for experimental studies and the Joanna Briggs Institute checklist for case reports. Key limitations included small sample sizes, variability in collection protocols, and the lack of validated field methods. Overall, the findings highlight the need for methodological integration and standardisation in forensic lubricant trace analysis. PROSPERO registration: CRD420251004301. No external funding was received.

1. Introduction

1.1. Background

Sexual violence remains a global public health concern and a key area of focus within forensic science, which requires the use of accurate and reliable methods for the collection and interpretation of evidence [1–3]. A comprehensive medical examination of the victim is essential and the evidence typically includes a medical report, DNA analysis, and the evaluation of physical traces [4,5]. In sexual assault investigations, seminal fluid represents a vital form of evidence, as it can establish a link to the perpetrator through DNA profiling [6,7]. However, DNA may not always be recoverable due to factors such as a prolonged interval between the incident and examination, the victim's post-assault actions (e.g., washing), or the deliberate use of condoms by perpetrators [8,9].

In such instances, forensic strategies may need to be adapted. This includes the use of intelligence-led approaches, advanced forensic technologies, digital forensics, and collaboration with Independent Sexual Violence Advisors (ISVAs) to enhance the effectiveness of evidence recovery [10–14].

The use of condoms during sexual assault can affect both the type and interpretation of available forensic evidence. Condom-related evidence becomes especially important when a victim reports assault, but no identifiable biological material from the suspect is present [15]. As awareness of DNA analysis increases, more offenders reportedly use condoms to prevent the deposition of biological traces and thus avoid detection [16]. According to the literature, between 7.5 % and 14.4 % of sexual assaults (i.e., vaginal or anal penetration) involve condom use [15,17,18]. This highlights the importance of detecting and analysing lubricant traces from condoms, as they may provide valuable forensic

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evidence in the absence of other biological traces [19].

A promising approach involves the detection of condom lubricant residues in latent fingermarks at sexual assault crime scenes. For instance, a recent study used Desorption Electrospray Ionisation Mass Spectrometry (DESI-MS) to detect and identify condom traces on cyanoacrylate-fumed fingerprints. The method demonstrated a classification accuracy of 90.9 % across 32 commercially available condom brands. Each condom brand exhibited distinct chemical signatures, often containing compounds such as polyethylene glycol (PEG) and polydimethylsiloxane (PDMS). The use of Principal Component Analysis (PCA) in combination with Linear Discriminant Analysis (LDA) enabled reliable classification of the samples [20].

In addition to fingermark analysis, other studies evaluated the detection of a wider range of condom-related trace evidence within biological matrices. This includes the detection of condom lubricant residues in vaginal or rectal swabs collected from sexual assault victims [16,21,22]. The presence of such residues may corroborate accounts of non-consensual sexual activity and strengthen the victim's testimony [23,24]. Furthermore, their persistence in biological matrices may assist in estimating the time since intercourse, aiding event reconstruction and timeline determination [25].

Lubricants and spermicides are widely used in condom manufacturing, and their detection can be indicative of condom use [26]. Different manufacturers use varying formulations of silicone-based or water-based lubricants, all of which have been thoroughly characterised [27–29]. PDMS, the most prevalent lubricant component, is found in over 95 % of condoms currently available on the market [30]. Water-based lubricants often contain hydrophilic agents such as glycerol, propylene glycol, and PEG [31,32], while nonoxynol-9 is commonly added for its spermicide properties [33].

Previous studies have demonstrated the feasibility of detecting condom residues in several forensic samples, including used condoms, lubricant residues, vaginal or anal swabs, penile swabs, and swabs from clothing [21,28,34]. A wide range of analytical techniques has been applied for this purpose, including:

(1) Spectroscopic methods, such as Fourier-Transform Infrared (FTIR) Spectroscopy and Raman spectroscopy [35–39];
(2) Mass spectrometric methods, such as Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC/MS), Gas Chromatography-Mass Spectrometry (GC–MS), Liquid Chromatography-Mass Spectrometry (LC-MS), Direct Analysis in Real Time Mass Spectrometry (DART-MS), and Matrix-Assisted Laser Desorption/Ionisation Time-of-Flight Mass Spectrometry (MALDI-TOF MS), which offer high sensitivity and specificity for analysing lubricant components [34,40–42];
(3) Microscopic methods, used to visualise condom traces on smears and surfaces [21,22,43].

These techniques differ in terms of analytical performance, ease of use and sample compatibility, which may impact their forensic applicability.

1.2. Research problem and rationale

Although several methods have been proposed for detecting condom residues, relatively few have been specifically validated within the vaginal matrix [44–46]. Such validation is critical to ensure their applicability in real forensic casework.

This systematic review aims to evaluate current methods for detecting condom residues in human biological samples, focusing on the analytical effectiveness and forensic reliability of these methods in identifying condom use during sexual contact. By synthesising the available evidence, the review seeks to clarify their forensic relevance, identify methodological gaps, and suggest areas requiring further investigation.

2. Materials and methods

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [47]. It was registered with PROSPERO (International Prospective Register of Systematic Reviews) under ID: CRD420251004301(https://www.crd.york.ac.uk/PROSPERO/view/CRD420251004301). The PRISMA 2020 flowchart (Fig. 1), generated using the PRISMA 2020 R package [48], illustrates the study selection process. The PRISMA 2020 checklist is available in Supplementary Material (Table S1).

2.1. Eligibility criteria

Eligibility criteria were developed using the PICO(S) framework. Studies were included if they met all the following criteria:

1. Original, empirical research, including cohort studies, experimental designs, and forensic case reports involving the detection of condom traces in human biological matrices (the term 'biological matrix' refers to biological substrates such as vaginal swabs, simulated semen samples, or pooled post-intercourse fluids, depending on study context);

2. Published from 1 January 2020 onwards in peer-reviewed scientific journals;
3. Written in English.

Studies were excluded if they:

1. Focused solely on condom composition without reference to human biological samples;
2. Included participants under the age of 18 or did not involve documented sexual contact;
3. Were non-empirical publications (e.g., commentaries, editorials, letters, reviews, book chapters);
4. Were published prior to 2020;
5. Were not peer-reviewed or not written in English;
6. Did not provide access to the full text.

A five-year time window was deliberately chosen to capture studies reflecting recent advances in analytical methods and directly relevant to current forensic casework. This a priori cut-off aligns the review with post-2019 developments in spectroscopic and mass-spectrometric workflows and current forensic evidentiary standards; relevant pre-2020 studies are cited for context but were excluded from the narrative synthesis due to methodological non-comparability with contemporary platforms.

The research question was formulated using the PICO(s) framework, as follows:

Population (P): Adults (≥18 years) who have engaged in sexual contact involving condom use.

Intervention (I): Detection of condom residues in human biological samples using analytical methods.

Comparison (C): Performance comparison of different analytical detection methods.

Outcomes (O): Accuracy and reliability in confirming sexual contact and evidentiary value.

Study Design (S): Cohort studies, forensic case reports, and experimental studies.

Research Question: In adults (P) who have engaged in sexual contact using condoms, how do analytical methods (I) compare (C) in terms of their effectiveness and reliability (O) in detecting condom residues in human biological samples, based on cohort, case, and experimental study designs (S)?

PICO(S) search strategy is presented in Supplementary Material, Table S2.

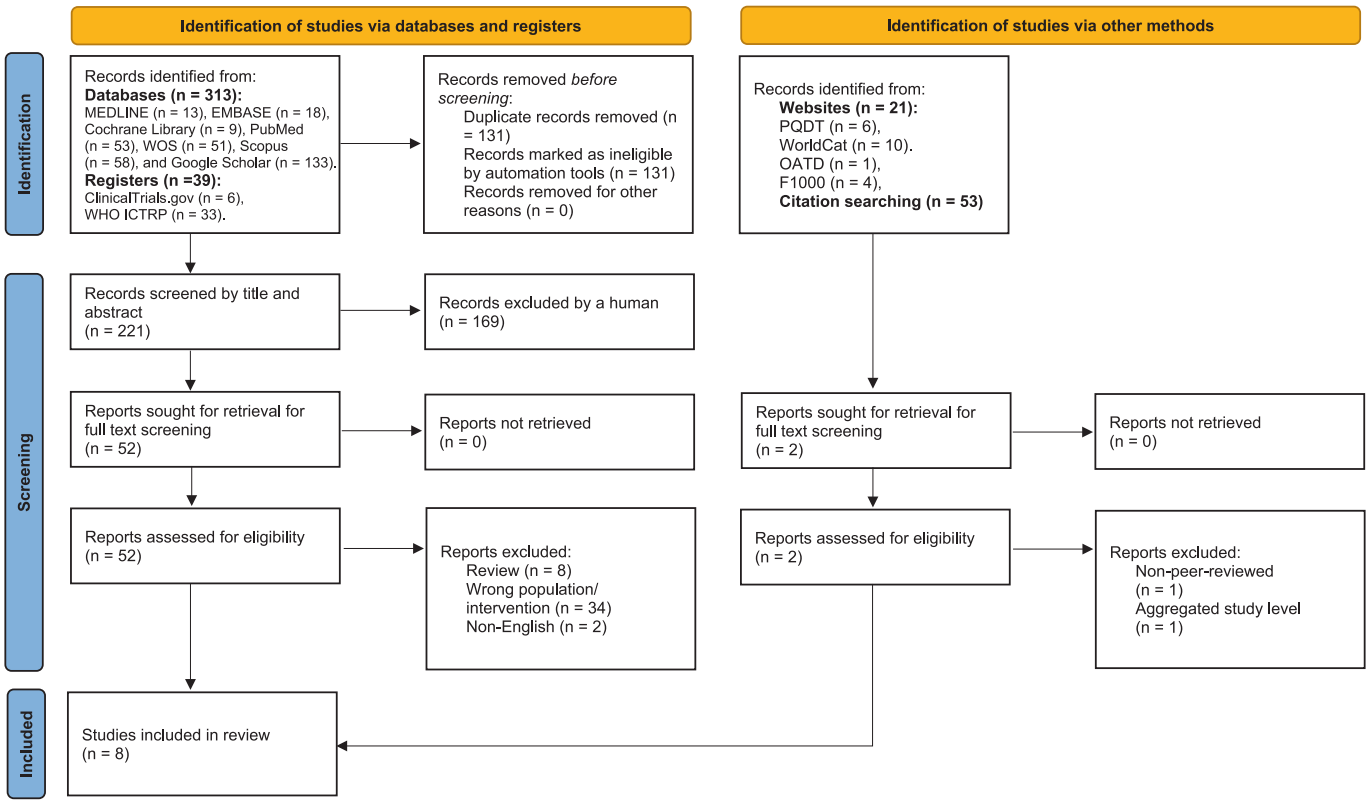

Fig. 1. PRISMA flow diagram illustrating identification, screening, and inclusion of studies.

2.2. Information sources

Searches were conducted across seven electronic databases: MEDLINE (Ovid), EMBASE (Ovid), Cochrane Library (CENTRAL), PubMed, Web of Science (Clarivate Analytics), Scopus (Elsevier), and Google Scholar. Two trial registers were also searched: ClinicalTrials.gov and the World Health Organisation International Clinical Trials Registry Platform (WHO ICTRP). Grey literature sources included three websites: ProQuest Dissertations & Theses (PQDT), WorldCat, Open Access Theses and Dissertations (OATD). Conference proceedings were retrieved from Scopus and Web of Science Conference Proceedings Citation Index (CPCI-S), while preprints were identified through F1000 Preprints.

Citation chasing was performed in Web of Science (Core Collection), Scopus, Google Scholar, Semantic Scholar, ResearchGate, and Citation Chaser. The tables of contents of key forensic journals were manually searched for studies published between 1 January 2020 and 28 February 2025, to identify recently published studies that had not yet been indexed. This manual search yielded no additional eligible studies. The review included studies published on or after 1 January 2020. 'Cited by' alerts in Google Scholar were monitored, and the final search was completed on 28 February 2025.

Grey literature was included to capture emerging analytical methods not yet published in peer-reviewed journals. However, such sources were considered only if methodologically rigorous and were evaluated using an adapted GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework [49], tailored to forensic science criteria. Details of the full search methodology are available in Supplementary Material, Tables S2 and S3.

2.3. Search strategy

Search terms were developed and refined with the guidance of an experienced research librarian, using the PRESS (Peer Review of Electronic Search Strategies) checklist [50]. Boolean operators were employed, and Medical Subject Headings [MeSH] terms were combined with free-text keywords. The following core terms and synonyms were used: 'condom traces', 'lubricant residue', 'polydimethylsiloxane (PDMS)', 'sexual contact', 'post-coitus samples', 'human biological samples', 'vaginal matrix', 'detection methods', 'spectroscopy', 'mass spectrometry', 'infrared spectroscopy', 'forensic evidence'. Database-specific search strategies are provided in Supplementary Material, Table S4.

2.4. Selection process

References were imported into EndNote 21 (Clarivate, UK) for citation management and automatic de-duplication. Titles and abstracts were screened using Rayyan AI (Qatar Computing Research Institute) by two reviewers (SM and LA), working independently and blind to one another's decisions. Records were coded as 'yes' (eligible), 'no' (ineligible), or 'maybe' (unclear). Full-text screening was conducted for articles that were potentially eligible. Potential overlap or derivation across publications from the same research groups was assessed at full-text screening (author lists, setting, sampling frame, timeframe, and biological matrices). Where overlap was identified, a single primary report was retained for data extraction and synthesis. Companion or derivative publications were used solely to provide contextual information (e.g., methodological details) and were not counted as additional studies or included in any synthesis, thereby avoiding double-counting.

Eligibility assessments adhered to PRISMA 2020 guidance [47]. Discrepancies were resolved by consensus or arbitration by a third reviewer (NF) [51]. A complete list of excluded studies with reasons is included in Supplementary Material, Table S5.

The original PROSPERO registration (CRD420251004301) has been updated to reflect refinements made during the pilot testing phase. These include: (1) minor modifications to the PICO(S) framework for increased clarity and relevance to the forensic practice; (2) a revised research question to align more closely with identified data; and (3)

standardisation of terminology (https://www.crd.york.ac.uk/PROSPERO/view/CRD420251004301#:~:text=Version%201.0%2C%20published%2007%20Mar%202025). These amendments do not affect the scope, objectives, or methodological integrity of the review and are documented in Table S6 of the Supplementary Material.

2.5. Data extraction

Data was extracted independently by two reviewers (SM and LA) using a piloted standardised Data Extraction Form (DEF). Discrepancies were resolved through discussion, and where necessary, arbitration by a third reviewer (NF). Extracted information included: study characteristics (authors, year, country, journal), methodology (analytical technique, sample collection, instrumentation), target components (PDMS, PEG), study outcomes (Limit of Detection (LoD), sensitivity, specificity), and practical implications (forensic applications, evidentiary value). Effect measures included quantitative thresholds such as LoD, persistence time, and sensitivity/specificity metrics where available. Where quantitative measures were not provided, inferential qualitative descriptors ('confirmatory', 'partial discrimination') were extracted to enable narrative synthesis. For the narrative synthesis, outcomes were stratified by study design (laboratory/experimental versus case reports), and findings are presented in separate subsections to distinguish experimental performance from casework applicability. Automated data extraction tools were not used. Where reported, information on ethics approval, participant consent, and anonymisation procedures was extracted. These were tabulated to assess ethical transparency across studies.

2.6. Risk of bias assessment

Risk of bias was assessed using two tools matched to the study design. For analytical laboratory studies, QUADAS-2 (Quality Assessment of Diagnostic Accuracy Studies) tool was applied [52]. For case reports, the Joanna Briggs Institute (JBI) Critical Appraisal Tool was used [53].

The assessments focused on design, sample handling, data analysis, and reporting quality. Risk of bias and conflicts of interest were also taken into consideration. Assessments were performed by two independent authors (SM and LA). Any disagreements were resolved through discussion, with arbitration by a third author if necessary (NF).

2.7. Certainty of evidence

The certainty of the evidence was assessed using the GRADE framework [49]. This approach evaluates five domains: risk of bias, inconsistency, indirectness, imprecision, and publication bias. Overall certainty ratings were applied per analytical method.

2.8. Data synthesis: Subgroup and heterogeneity analysis

Due to considerable methodological heterogeneity, a quantitative *meta*-analysis was not feasible. No quantitative pooling was undertaken. Pooling of persistence outcomes was precluded by the small number of eligible studies; heterogeneity in study design, biological matrices, operational definitions, and timing of "persistence" as well as the frequent absence of compatible dispersion/precision statistics (e.g., standard deviations (SDs), standard errors (SEs), or confidence intervals (Cls)) required to compute comparable effect sizes. Consequently, a structured synthesis was undertaken in accordance with the SWiM (Synthesis Without Meta-analysis) guidelines [54]. Subgroup analyses were performed by (1) matrix type (vaginal swabs, simulated matrices, pooled semen with condom swatches); (2) analytical technique (DRIFTS-FTIR, ATR-FTIR, Py-GC/MS, sfPESI-MS, and GC–MS), and (3) lubricant type (silicone-based or water-based). Heterogeneity was assessed narratively, with attention to sample preparation, collection timing, matrix composition, and instrument parameters.

3. Results

A total of 426 records were retrieved. Of these, 313 records were identified through seven electronic databases: MEDLINE (n = 13), EMBASE (n = 15), Cochrane Library (n = 9), PubMed (n = 53), Web of Science (n = 51), Scopus (n = 58), and Google Scholar (n = 114). An additional 39 records were retrieved from two registers: ClinicalTrials.gov (n = 6) and the WHO ICTRP (n = 33). A further 21 records were identified via alternative grey sources, including: PQDT (n = 6), WorldCat (n = 10), OATD (n = 1), and F1000 (n = 4). Citation searching yielded 53 additional records.

A total of 313 records identified through databases and registers were imported into EndNote 21 (Clarivate, UK) for deduplication, resulting in the removal of 131 duplicates. The remaining 221 records were screened by title and abstract, resulting in the exclusion of 169 as irrelevant. Fifty-two full-text reports were independently assessed by two reviewers (SM and LA). Of these, 44 were excluded for the following reasons: review articles (n = 8), not meeting the inclusion criteria (n = 34), or published in a non-English language (n = 2).

Of the 74 records retrieved from alternative sources, 72 were excluded during the title and abstract screening process. Two underwent full-text screening, of which one was excluded because it was not peer-reviewed and one due to data aggregation. The PRISMA flow diagram (Fig. 1) illustrates this selection process. Ultimately, eight studies [55–62] were included in this review. No confirmed instances of duplicate use of identical participants or specimens for the target outcomes were identified. Where partial overlap could not be ruled out, studies were not combined in any synthesis; all studies were synthesised narratively.

3.1. Characteristics of included studies

The review included eight studies: four experimental [55–58], two case studies [59,60], and two comparative studies [61,62]. The experimental studies included both a cross-sectional component [55] and a longitudinal component [56,58]. The timeframe spanned from 2020 to 2024, with 50 % of studies published in 2021, 25 % in 2020, 12.5 % in 2023, and 12.5 % in 2024. Most studies (n = 5; 62.5 %)[55–57,59,61] were conducted in Switzerland, with others from India (12.5 %) [56], Italy (12.5 %) [58], and the UK (12.5 %) [60].

Sample sizes ranged from 4 [60] to 270 [53], totalling 501 samples. Condom brands per study ranged from 2 [56] to 25 [61]. Vaginal swabs were used in 87.5 % of studies [53–59]; one study [62] used pooled semen. A summary is presented in Table 1. The brief descriptions are provided solely to contextualise study-level heterogeneity in support of Table 1; they do not constitute a narrative synthesis, and no effect estimates are narratively pooled. The structured SWiM, along with the corresponding GRADE certainty assessments, is reported in Section 3.4, while the risk of bias evaluation is presented in Section 3.5.

No preregistered protocols or published study designs were identified for any of the included studies, which limited the ability to verify selective outcome reporting or deviation from prespecified methods.

Although this review focused on analytical methodologies, ethical oversight of included studies was also examined. A summary of ethics approval, consent procedures, and anonymisation practices is provided in Supplementary Material, Table S7. This addition enhances methodological transparency and pre-empts ethical reporting concerns commonly raised in reviews of studies involving human-derived materials. Common themes included the forensic relevance of condom trace detection. The research objectives varied; some studies evaluated analytical techniques, while others investigated interactions between lubricants and biological matrices.

Table 1
Key characteristics of the included studies.

Ref.	Author, year, country	Study type	Aim of study	Sample size	Condom brands	Analytical method (s)	Extraction solvent(s)	Detected component (s)	Main findings	Limitations	Conclusion
[55]	Saric et al., 2021, Switzerland	Experimental Study *(with Cross-Sectional Component)*	To investigate the classification of condom traces following their transfer in a vaginal matrix	270	11	DRIFTS-FTIR	Hexane	PDMS	Samples with silicone lubricants were visually indistinguishable. Donor variation had a greater impact on lubricant transfer than recipient characteristics.	Variability among volunteers affected results; ethical constraints limited control over conditions.	Detection of condom residues remains challenging due to overlapping spectral characteristics of silicone-based lubricants.
[56]	Fischer et al., 2021, Switzerland	Experimental Study *(with Longitudinal Component)*	To investigate the persistence of silicone lubricants from condoms in the vaginal matrix	33	2	DRIFTS-FTIR	Hexane	PDMS	PDMS were detectable up to 18 h post-coitus; exponential decay observed.	The small sample. Variability introduced by self-sampling methods.	Silicone lubricants are detectable for up to 18 h, influenced by individual factors and activities.
[57]	Burnier C, Favre V. et al., 2021, Switzerland	Experimental Study	To optimise DRIFTS-FTIR parameters for forensic analysis of silicone lubricants	132	16	DRIFTS-FTIR	Hexane, Dichloro methane	PDMS	DRIFTS-FTIR optimised for 64 scans; limited brand discrimination observed.	Limited brand differentiation and small sample size affected generalisability.	DRIFTS-FTIR showed strong potential for PDMS detection but lacked discriminatory power between brands.
[58]	Sharma et al., 2024, India	Experimental Study *(with Longitudinal Component)*	To enhance forensic discrimination of condom lubricants using ATR-FTIR	10	25	ATR-FTIR	–	PDMS; PEG; Glycerin	ATR-FTIR distinguished lubricants with 100 % accuracy; the method proved robust against contaminants.	Small sample size; individual differences could introduce inconsistencies.	ATR-FTIR enables robust differentiation of lubricant types and demonstrates resilience against biological interference.
[59]	Burnier, Kelly et al., 2021, Switzerland	Case Report	To enhance analysis of condom evidence in sexual assault cases using py-GC–MS and GC–MS	8	4	Py-GC/MS; GC–MS	Hexane; Methanol and diphenylmethane; Methanol	Silicone	The validated framework effectively differentiates condom profiles, indicating that the presence of silicone residues confirms condom use.	Interpretation was hindered by a lack of standardised protocols and variable lubricant persistence.	Findings support the implementation of Py-GC/MS and GC–MS as complementary tools in lubricant residue analysis.
[60]	Tozzo et al., 2023, Italy	Case Report	To enhance forensic investigations of sexual assaults using condom lubricant residues	4	20	ATR-FTIR; GC–MS	Trichloro-methane	PDMS	Lubricant residues supported the victim's account; effective detection over time.	A single-case study limits generalisability; potential interference from biological fluids.	Residue persistence supports evidentiary value even in the absence of male DNA.
[61]	Burnier, van Bronswijk et al., 2020, Switzerland	Comparative Study	To compare spectroscopic methods for detecting PDMS in forensic samples	36	25	ATR-FTIR; DRIFTS-FTIR; micro-ATR-FTIR; transmission FTIR; micro-transmission FTIR; Raman spectroscopy	Hexane	PDMS	DRIFTS-FTIR yielded the clearest spectral data with persistence observed up to 18 h post-coitus.	Variability in spectral parameters affects reproducibility; sample generalisability concerns.	DRIFTS was the most effective method for detecting PDMS in forensic samples.
[62]	Rankin-Turner et al., 2020, UK	Comparative Study	To evaluate sfPESI-MS for rapid analysis of sexual assault evidence	8	8	sfPESI-MS	Ethanol	Amino acids; PDMS; PEG	Unique chemical profiles for each condom brand identified; key ions determined.	Ion suppression from lubricants; limited sample diversity; aging effects not explored.	sfPESI-MS provided rapid, brand-level discrimination based on unique chemical profiles, with minimal sample preparation.

3.2. Findings from laboratory/experimental studies

Saric et al. [55] investigated condom lubricant transfer to the vaginal matrix, using Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS-FTIR). Samples were collected via vaginal swabs post-intercourse, followed by extraction to isolate condom lubricants. Residues of condom lubricants within the vaginal matrix were expected but not consistently detected, suggesting potential limitations in the sensitivity of the DRIFTS-FTIR method or variability introduced during sample preparation. The study concluded that the condom type influenced transfer variability more than the vaginal environment. PCA analysis indicated water-based lubricants could be chemically distinguished, while silicone-based lubricants could not. These unique chemical signatures enabled brand-level identification.

Fischer et al. [56] evaluated the persistence of PDMS in the vaginal matrix using DRIFTS-FTIR. PDMS, the primary silicone-based lubricant investigated, was detectable for up to 18 h post-coitus. The research highlighted the influence of various factors on the persistence, including elapsed time between intercourse and.

sample collection, and the post-coital activities, such as resting or showering. It revealed that approximately 50 % of the PDMS signal was lost within the first hour, with detection becoming inconsistent after 24 h, as interference from the vaginal matrix began to dominate after 36 h. The variability in the detection of PDMS among participants indicated that individual factors, including specific post-coital activities, significantly influenced the persistence of silicone lubricants detected in the vaginal matrix. These findings underscore the need for improved statistical modelling, increased sample sizes, and reduced variability to enhance the understanding and interpretation of these dynamics in forensic contexts.

Burnier et al. [57] optimised DRIFTS-FTIR for detecting silicone-based lubricants in vaginal matrices. Conditions were adjusted (e.g., 64 scans at 4 cm^{-1} resolution). Despite improved signal-to-noise ratio (SNR), brand-level differentiation was not achieved. Varying preparation techniques were tested, confirming PDMS detectability but limited brand discrimination.

Sharma et al. [58] used ATR-FTIR with chemometrics on 25 condom brands. The method effectively distinguished between condom lubricants and commonly used household lubricants, including products such as glycerine-based and petroleum jelly lubricants, achieving 100 % accuracy, even in the presence of contaminants like vaginal fluid and menstrual blood.

Burnier, van Bronswijk et al. [61] compared five FTIR (ATR, micro-ATR, DRIFTS, transmission, and micro-transmission) techniques and Raman spectroscopy. DRIFT provided superior detection of PDMS in cotton swabs, particularly in post-coital samples where lubricant residues were recovered from the vaginal matrix up to 18 h after intercourse. Raman spectroscopy lacked key spectral peaks associated with the Si-O-Si (silicon-oxygen-silicon) and Si-C (silicon-carbon) bonds, which are characteristic vibrational features of PDMS, the principal compound in silicon-based lubricants. Self-sampled cotton swabs from four volunteers were used, including background (pre-coital), immediate post-coital, and delayed post-coital swabs (6 to 24 h), which enabled the assessment of persistence and the method's applicability to real forensic scenarios.

Rankin-Turner et al. [62] employed sheath-flow probe electrospray ionisation mass spectrometry (sfPESI-MS) for the rapid, preparation-free analysis of semen and condom residues in forensic samples. Semen and several condom brands were analysed directly without sample preparation. Unique profiles enabled brand discrimination within 10 s.

3.3. Findings from case reports

Two case reports [59,60] were summarised to illustrate operational feasibility and evidentiary interpretation in real-world investigations; these findings were not pooled with laboratory performance data.

Burnier, Kelly et al. [59] validated Py-GC/MS and GC–MS using two case studies. In one case, PDMS residues were detected on the high vaginal swab submitted for forensic analysis, despite the absence of male DNA, which is not uncommon when condoms are used during assault, yet the detection of PDMS corroborated the complainant's account. In the second case, a used condom was recovered from the victim's clothing, but no silicone or water-based lubricant residues were detected in the high vaginal swab, despite analysis by both Py-GC/MS and GC–MS. The authors attributed this to factors such as a possible non-lubricated condom, delayed evidence collection (≥20 h post-assault), or insufficient trace transfer.

Tozzo et al. [60] analysed condom lubricant residues in a sexual assault case using FTIR and GC–MS on vaginal swabs previously processed for DNA and mRNA analysis. Short Tandem Repeat (STR) and mRNA analysis showed only the victim's profile. PDMS was detected on the swabs, with chemical signatures matching those found in a condom of the same brand and model recovered from the suspect's residence. A Likelihood Ratio (LR) was used to quantify evidentiary weight. Combining both techniques enhanced evidentiary robustness.

3.4. Structured synthesis of results, certainty assessment, and subgroup analysis

Certainty of evidence was assessed using the GRADE framework, as summarised in Table 2. Overall, infrared spectroscopy techniques demonstrated moderate to high certainty, with DRIFTS-FTIR achieving the highest rating based on low risk of bias, consistency across studies, and direct applicability to forensic scenarios. Certainty was moderate for ATR-FTIR and GC–MS, largely due to limitations in imprecision and indirectness. For sfPESI-MS, certainty was rated as very low, due to its evaluation in a single proof-of-concept study with high risk of bias and limited validation.

Due to considerable methodological and biological heterogeneity, the findings from the included studies were synthesised narratively using the SWiM framework. Studies were grouped by matrix type, analytical method, and lubricant composition. A narrative heterogeneity assessment highlighted variability in sampling protocols, collection timing, matrix type, and analytical platforms.

Reported LoD values for PDMS, the principal analyte in silicone-based lubricants, ranged from 1 μg/mL [58] to an inferred 30 μg/mL [56], depending on the analytical technique and biological matrix. Reported analytical sensitivity for detecting PDMS under controlled laboratory conditions reached 100 % using ATR-FTIR on spiked vaginal swabs. Persistence of detectable PDMS signal extended up to 24 h post-coitus in FTIR-based studies [56–58], while immediate surface detection was demonstrated using sfPESI-MS [62]. Several studies have noted that biological variability in the vaginal matrix, including timing post-coitus and endogenous secretions such as menstrual fluid and epithelial debris, affects detection outcomes [55,56,61]. Sharma et al. [58] reported that ATR-FTIR remained effective despite the presence of menstrual fluid.

Table 3 presents a structured synthesis of key findings, aligned with SWiM guidance and stratified by method, sample matrix, and detection performance.

Outcome reporting was variable across studies. While several investigations provided complete data on LoD, sensitivity, and persistence, others reported only selected results or failed to quantify analytical performance (e.g., sensitivity or specificity). For instance, studies by Saric et al. [55], Fischer et al. [56], and Burnier et al. [57] reported detection success but did not provide full performance metrics, while Sharma et al. [58] presented complete accuracy data. These inconsistencies reduce comparability and may indicate a risk of selective reporting.

3.5. Risk of bias evaluation

Risk of bias was assessed using two validated tools tailored to study

Table 2
Certainty of evidence per analytical method based on GRADE assessment.

Analytical method	Number of studies	Risk of bias	Inconsistency	Indirectness	Imprecision	Certainty (GRADE)
DRIFTS-FTIR	4	Low	Low	Low	Low	**High**
ATR-FTIR	3	Low	Low	Moderate	Moderate	**Moderate**
Py-GC/MS	2	Moderate	Low	Low	Moderate	**Moderate**
GC–MS	2	Low to moderate	Moderate	Low	Moderate	**Moderate**
Raman spectroscopy	1	High	High	Moderate	High	**Low**
sfPESI-MS	1	High	Serious (single study)	High	High	**Very Low**

Table 3
Comparative summary of analytical methods for condom residues detection (SWiM-aligned).

Ref.	Author, year	Matrix type	Analyticalmethod (s)	LoD for PDMS(μg/mL) *	Sensitivity/ Specificity	Persistence (hrs)	Study type	Summary findings
[55]	Saric et al., 2021	Vaginal (post-coital)	DRIFTS-FTIR	~10 *(inferred)*	Not reported	~18 (volunteer)	Experimental	PDMS-based lubricants detectable; differentiation between condom types not achieved.
[56]	Fischer et al., 2021	Vaginal (post-coital)	DRIFTS-FTIR	~25–30	Not quantified; signal drops ~50 % in 1 h	18—–24; not detectable after 36	Experimental	Reliable detection of PDMS within 18 h post-coitus; significant spectral decay thereafter; signal attenuated by vaginal matrix interference.
[57]	Burnier C, Favre V. et al., 2021	Vaginal	DRIFTS-FTIR	5–10	Not stated	Estimated 24	Experimental	Optimised PDMS-associated spectral bands (e.g., Si–CH_3, Si–O–Si); clearer lubricant signal; partial brand differentiation.
[58]	Sharma et al., 2024	Vaginal (controlled)	ATR-FTIR	1	100 % / 100 %for PDMS in vaginal matrix (lab)	>24 (controlled)	Experimental	Full classification accuracy; strong signal even in the presence of menstrual fluid.
[59]	Burnier, Kelly et al., 2021	Vaginal	Py-GC/MS; GC–MS	2	Not stated	~24	Case report	Confirmatory detection of PDMS in the absence of semen; support evidentiary linkage.
[60]	Tozzo et al., 2023	Vaginal	ATR-FTIR; GC–MS	2–5 (combined)	Qualitative (confirmatory)	Not reported	Case report	Combined methods validated case interpretation; increased reliability in absence of DNA.
[61]	Burnier, van Bronswijk et al., 2020	Vaginal (simulated)	ATR-FTIR; DRIFTS-FTIR; micro-ATR-FTIR; transmission FTIR; micro-transmission FTIR; Raman spectroscopy	5	Partial brand discrimination of PDMS-based lubricants	*18 h (simulated)*	Comparative study	DRIFTS-FTIR outperformed Raman spectroscopy; method required human validation; promising for non-invasive analysis.
[62]	Rankin-Turner et al., 2020	Simul ated (semen + swab)	sfPESI-MS	Not reported	High brand classification *(lab-based)*	Immediate contact only	Proof-of-concept	Surface residue identification successful; lacks validation for persistence and field use.

Note: *LoD (Limit of detection) value were estimated from spectral data or author commentary; not always explicitly reported in the source study.

design: the QUADAS-2 tool for analytical and observational studies [55–58,61,62] and the JBI Critical Appraisal Tool for case reports [59,60].The QUADAS-2 evaluation considered patient selection, index test, reference standard, and flow and timing. All studies assessed using this tool received a low risk of bias rating. The JBL tool assessed eight criteria, all of which were met in both case reports, resulting in low risk of bias evaluations. Full justification of ratings is available in Tables S8–S10 of the Supplementary Material. These assessments support the methodological quality of the included studies and contribute to the overall certainty of evidence presented in this review.

4. Discussion

Studies have demonstrated that condom use during sexual contact can result in the transfer of detectable forensic evidence in biological samples such as vaginal and penile swabs [4,11,13,46,63,64]. In line with SWiM guidance, a structured comparison is presented rather than a narrative summary. Findings are contrasted across biological matrices, analytical methods, and key outcomes (persistence, sensitivity, and limits of detection), with statements restricted to the direction and consistency of effects and accompanied by GRADE certainty ratings. Quantitative pooling was not undertaken due to methodological and reporting heterogeneity.

Within this context, forensic practitioners currently face three primary challenges: detecting the presence of condom-related traces; associating these traces with specific condom types [18,19,34,65], and validating analytical methods that are both effective on biological matrices and suitable for operational forensic casework [4,12,24,66,67]. Condom residues recovered during investigations often contain a complex mixture of compounds derived from both the condom formulations and the vaginal matrix [21,46,55–57]. The transfer and persistence of lubricants are influenced by multiple factors, including lubricant composition, recipient physiology (matrix characteristics and hormonal fluctuations), and coital parameters such as duration and pressure [21,25,55,56].

Silicone-based lubricants are generally more persistent and transfer

more readily than water-based variants [32,41,42,55,58,64,68]. Detection variability in the vaginal matrix is a recurring challenge across various analytical methods. While ATR-FTIR remained effective in the presence of menstrual fluid in controlled studies [58], other studies indicated that factors such as epithelial debris and time since intercourse can diminish signal clarity [55,56,61]. These findings underscore the need to account for the complexity of the biological matrix when developing detection protocols. PDMS concentrations influence trace detectability. While 500 mg of lubricant is typically applied per condom, not all is transferred, and matrix dilution lowers signal strength over time [20,30,43,56]. Fischer et al. [56] reported a 50 % drop in DRIFTS-FTIR signal intensity for PDMS within one hour post-intercourse. Similarly, Tottey et al. [25] observed time- and temperature-dependent degradation of PDMS, highlighting the need to account for environmental factors in forensic interpretation [44,68,73,74].

The sfPESI-MS method introduced by Rankin-Turner et al. [61] allows for a rapid in situ detection of condom residues but requires costly instrumentation and further validation [14,60,69]. Time delays between intercourse and evidence collection also introduce analytical challenges [7,14,61,70,71]. For instance, Fischer et al. [56] found that PDMS signal declines rapidly within the first hour post-coitus, making detection unreliable beyond 24–36 h. These findings reflect broader evidence that PDMS degrades over time within biological matrices, reducing its forensic value [21,46,55,72]. Importantly, several studies found that the presence of semen or saliva does not interfere with the analysis of condom lubricants such as PDMS [7,36]. However, biological variability in the vaginal matrix, particularly related to menstrual phase, pH, and the presence of mucosal secretions, may still influence spectral resolution and complicate analytical interpretation [55,57,58].

DRIFTS-FTIR and ATR-FTIR remain the most established tools for condom residue detection [35,46,57,73,75]. DRIFTS-FTIR yields high-quality spectra but is sensitive to sample preparation conditions. ATR-FTIR offers reproducibility and resilience against contamination, yet it faces challenges in differentiating to differentiate between chemically similar substances [35,55,63,75,76]. Sharma et al. [58] reported 100 % classification accuracy using ATR-FTIR and chemometrics, reinforcing its utility in lubricant discrimination.

Py-GC/MS provides detailed compositional analysis and high sensitivity to non-volatile compounds [46,77,78]. However, its utility in condom trace analysis remains limited by a lack of standardised parameters and insufficient validation studies [79,80]. Despite these limitations, Py-GC/MS can complement FTIR methods, particularly for complex mixtures requiring separation.

Notably, studies employing combined techniques (ATR-FTIR with GG-MS) in Tozzo et al. [60], and multi-modal spectroscopy in Burnier et al. [59] demonstrated improved confirmatory power and enhanced evidentiary reliability. These hybrid approaches allow for cross-validation and compensate for matrix-related artefacts.

The persistence of condom traces is affected by post-coital behaviours such as hygiene, douching, and physical activity [19,21,25,55,56]. Such factors may shorten the detection window. Hence, controlled persistence studies and broader participant recruitment are needed to enhance the generalisability of current findings.

Sample collection remains a significant source of variability in analytical outcomes. Studies employing self-sampling protocols have demonstrated considerable procedural inconsistency due to variable swabbing pressure and technique, which contrasts with standardised methods typically used in forensic settings [32,64,71,73]. Solvent-based extraction, particularly with hexane, was consistently required for efficient PDMS recovery. However, DNA extraction before solvent extraction was found to compromise lubricant trace detectability [73]. Current forensic evidence kits are not optimised for recovering condom-related residues [14,15,60]. Mbo et al. [63] proposed including a dedicated swab for lubricant detection in standard rape kits, a recommendation echoed by multiple researchers [24,46,55,64,71]. Integrating validated swabbing protocols into forensic standard operating procedures (SOPs) would reduce variability and improve the reliability of trace evidence analysis.

This variability is further compounded by the absence of standardised SOPs across laboratories and medical collection teams. Establishing such protocols is critical for enhancing cross-jurisdictional consistency and evidentiary admissibility.

Despite ethical approval being reported in most experimental studies, challenges surrounding informed consent and participant variability in forensic research persist [15,36,71]. Studies such as those by Fischer et al. [56] and Burnier et al. [61] relied on self-sampling by volunteers, which, although ethically permissible, introduces variability in compliance, technique, and physiological factors, including menstrual phase, mucosal secretions, and recent sexual activity. In contrast, Burnier et al. [57] did not report ethical procedures, highlighting inconsistent documentation across the literature. Forensic studies involving sensitive biological matrices, particularly vaginal or anal swabs, require robust ethical safeguards and transparent reporting to ensure participant protection and methodological reproducibility. As this area of research advances, greater standardisation in ethical documentation and reporting is essential for maintaining scientific and ethical integrity.

Policy reforms are recommended to standardise residue collection procedures across jurisdictions. National forensic frameworks should include updated training modules on lubricant trace recovery and interpretation. Emphasising trace analysis in non-DNA cases may support more inclusive and successful investigations.

5. Limitations

5.1. Limitations of the review

This review employed a comprehensive search strategy, including grey literature and trial registries. However, no eligible studies from grey literature sources met the inclusion criteria. Only peer-reviewed studies published in English from 2020 onwards were included. This ensured methodological consistency but narrowed the temporal and linguistic scope. Accordingly, conclusions are limited to contemporary (post-2019) forensic analytical workflows and may not fully generalise to earlier techniques or condom formulations. Earlier pre-2020 studies are cited for context but were not pooled.

A distinction was made between evidence obtained under controlled laboratory conditions and that derived from case reports. Laboratory findings were interpreted as measures of analytical performance, whereas case reports were considered in terms of operational feasibility and evidentiary interpretation. The limited number of included studies reduced the breadth of synthesis and hindered generalisability. Owing to the small sample size and methodological heterogeneity, formal assessment of reporting bias (e.g., funnel plots or small-study effect tests) was not feasible.

5.2. Limitations of the included studies

The included studies varied substantially in design, sampling procedures, lubricant composition, and analytical approaches. A residual risk of unrecognised dataset overlap remains where it was not possible to confirm independence across studies. Therefore, laboratory/experimental studies were synthesised separately from case reports (Sections 3.2 and 3.3). Laboratory results were interpreted as estimates of analytical performance under controlled conditions, whereas case reports were used to inform applicability to casework and evidentiary interpretation; generalisation from laboratory performance to operational settings was not assumed. Additionally, key outcomes, such as persistence, were reported using non-comparable definitions and lacked compatible dispersion/precision statistics (e.g., SDs, SEs, CIs), precluding any *meta*-analysis.

Most were laboratory-based and lacked validation in operational

forensic contexts. Performance metrics, such as LoD, sensitivity, and specificity, were often missing or inconsistently reported, precluding *meta*-analytic synthesis. No study protocols or preregistration entries were available, thus limiting assessment of selective outcome reporting. Although ethical approval was stated in all human studies, reporting of informed consent and anonymisation procedures was inconsistent. Selective reporting of successful outcomes, with limited mention of non-significant results, suggests a risk of publication or methodological bias and limits cross-study comparability.

6. Future directions

Further research should prioritise larger sample sizes, diverse populations, and longitudinal assessments of lubricant degradation. Investigating physicochemical interactions between lubricants and biological matrices, and applying multivariate statistical tools (PCA, cluster analysis), may enhance discrimination accuracy. The development of validated SOPs for post-assault evidence collection, trace recovery, and analytical processing remains a critical priority. These SOPs should be tested through inter-laboratory validation studies and integrated into routine forensic workflows.

7. Conclusion

This systematic review provides an overview of current analytical approaches for detecting condom lubricant residues in a forensic context, with particular focus on sexual assault cases. The included studies collectively demonstrate that modern spectroscopic and chromatographic techniques (most notably DRIFTS-FTIR, ATR-FTIR, GC–MS, AND Py-GC/MS) are capable of identifying condom-related residues in biological matrices with varying degrees of sensitivity, specificity, and reliability.

The review highlights that the success of trace detection is influenced by several parameters, including the physicochemical composition of lubricants, biological variability of the matrix, sampling methodology, and post-coital interval. Despite promising technological advances, analytical inconsistencies persist due to limited standardisation across studies and a lack of robust validation in real-world forensic casework.

Critically, the findings highlight the potential of integrating multiple validated analytical techniques, supported by standardised protocols, to increase evidentiary robustness when conventional biological materials (e.g., DNA) are absent or degraded. Hybrid analytical approaches, notably those combining spectroscopic and chromatographic techniques, offer more robust evidentiary strength and should be prioritised in forensic workflows. The review acknowledges the importance of obtaining ethical approval and reporting results transparently in studies involving human-derived samples, although these aspects were not uniformly documented across the included literature.

In conclusion, the detection of condom traces represents a valuable adjunct to the forensic toolkit, offering corroborative evidence in complex investigations. Strengthening the analytical and procedural frameworks that underpin such detection is essential for enhancing the reliability and admissibility of non-DNA trace evidence in forensic practice.

CRediT authorship contribution statement

Saule A. Mussabekova: Writing – original draft, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Nunzianda Frascione:** Writing – review & editing, Validation, Conceptualization. **Laura B. Assylbayeva:** Writing – review & editing, Visualization, Data curation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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