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Identification of condoms and lubricants by FTIR spectroscopy and creation a database

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Abstract

Biological evidence plays a crucial role in establishing a connection between the victim and the suspect in cases of sexual assault. However, the use of condoms during such offenses significantly reduces the likelihood of obtaining DNA from biological samples. In these instances, the detection of chemical residues, such as lubricants, obtained through genitorectal examinations of the victim, can serve as evidence of condom use and support the assertion that the offense was committed with a condom. Particularly in cases where DNA evidence is unavailable, identifying the presence of lubricants or their substitutes within condom residues or as directly applied substances can help establish a link between the victim and the suspect. This study aimed to create a comprehensive lubricant database by analyzing various condom brands, lubricant gels, and alternative substances that can function as lubricants using Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy (ATR-FTIR) spectroscopy. The results demonstrated that Infrared (IR) spectra effectively differentiate condom brands and types, as well as lubricant gels and comparable substances, enabling the identification of their chemical compositions. Consequently, a database was developed for the forensic identification of condoms and lubricants recovered from crime scenes, to enhance the forensic investigation and elucidation of sexual assault cases.

Keywords: Forensic science, sexual assault, physical evidence, condoms, lubricants, database

Introduction

In cases of sexual assault, various types of physical evidence, including semen, blood, and lubricants, may be transferred to the victim or to the crime scene. Biological evidence such as blood, semen, hair, saliva, and urine are usually collected from the victim for DNA analysis. In recent years, there has been an increase in the use of condoms by perpetrators of sexual offences to avoid leaving biological evidence at the crime scene [1]. For this reason, DNA, which is of great importance on the way to the perpetrator, is either not available at all or is not available in sufficient quantities for analysis. In cases where DNA is available but there is a need for evidence to support the result of the analysis, evidence is important for the result of the investigation to be more precise. In addition, when there is no physical evidence at the crime scene to obtain DNA, the presence of evidence has much more importance for the investigation [2]. In some cases, even a small amount of lubricant found in a vaginal and/or anal swab sample taken from the victim is sufficient for the examination. This examination can establish a link between the victim and the perpetrator by detecting traces of lubricant from the condom. This trace evidence may originate from the condom or the use of personal lubricant. It is known that the components of lubricants or additives used in condoms of different brands vary considerably. For this reason, as in other cases, in cases of sexual assault, the evidence of genitorectal examination of the victim and the presence of any traces of condom and/or lubricant use may support a history of sexual intercourse with condom and lubricant use [1]. Apart from commercially used lubricants; various oils or creams are also known to be used as lubricants [2,3]. In the study published by Verma, for example; in a case where a four-year-old girl was allegedly sexually assaulted, it was reported that jelly/cream was used as a lubricant and may have been applied to the genital area of the child; samples taken from the child were analysed by IR spectroscopy to document the presence of traces

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of the jelly/cream in question. It enabled the identification of petrolatum an also Gas Chromatography-Mass Spectrophotometry (GC-MS) confirmed the presence of Methyl Stearate. The results of this investigation are contextual and strongly suggest that a jelly composition containing petrolatum and methyl stearate as ingredients was in fact applied to the child's genital area and its presence was also confirmed on the child's underwear [4].

Lubricants, which are chemicals found on the surface of condoms, help to characterize condoms. The chemical compounds contained in each brand of lubricant are specific. To group these materials, in general terms, silicone-based lubricants are composed of polydimethylsiloxane (PDMS), Polyethylene Glycol (PEG)-based lubricants are usually in the form of PEG-8, and water-based lubricants are composed of de-ionized water and glycerin [5]. By making use of this difference, in cases of sexual assault, it is possible to analyze the condom or lubricant found at the crime scene or the vaginal and/or anal swab sample taken from the victim by various spectroscopic methods in forensic science laboratories [6-8].

One of the spectroscopic methods used for lubricant analysis is Fourier Transform Infrared (FTIR) spectroscopy. The FTIR spectrophotometer used in this method is widely used in the determination of lubricants as well as in the analysis of many materials, since the analysis can be repeated in a very short time, precisely and accurately, without damaging the sample, without long sample preparation processes [9].

In this study, a database of condom brands, which are widely used in Türkiye and can be easily supplied by many people, and substances used as lubricant gel or commercial lubricant and 8 different substances that can be used as lubricant (olive oil, baby oil, petroleum jelly, cream types, and beeswax) was created by using IR spectroscopy and it was aimed to make inter-brand identification.

Material and Methods

In this study, no experimental study was performed on humans or human samples and no ethics committee approval was required since only inanimate objects were used.

Collection of Samples

In the study, to prepare a database for the characterization of condoms and lubricants in forensic sciences, the brands sold in Türkiye were obtained. While selecting condom and lubricant brands, brands that are accessible by everyone were preferred. On the other hand, the types of condoms and lubricants sold in easily accessible places such as supermarkets, pharmacies, health centers, cosmetic product sales companies and internet shopping platforms were included in the study. In total, 69 condom samples belonging to 16 brands, 39 lubricant gels belonging to 16 different brands and 8 different substances that can be used as lubricant (olive oil, baby oil, petroleum jelly, cream types, and beeswax) were analyzed (Figure 1, Tables 1-3). Beeswax was included in this study because it is possible to obtain a cream that can be specially prepared with olive oil for example baby face cream, protective care hand cream manufactured by such well-known brands globally.

Table 1. List of condom samples

No	Condom brand	Type	No	Condom brand	Type	No	Condom brand	Type
1	Anti-m	Classic	**24**	Fe	Nano thin	**47**	Okey	Ultra hisset (ultra feel)
2	Anti-m	Flavoured	**25**	Fe	Night vision	**48**	Okey	Zero
3	Anti-m	Ribbed	**26**	Fiesta	Classic	**49**	Okey	Zirve (peak)
4	Anti-m	Super dotted	**27**	Fiesta	Dotted	**50**	Parachute	Klasik (classic)
5	Dodo	Classic	**28**	Fiesta	Strawberry	**51**	Parachute	İnce (thin)
6	Dodo	Dotted form	**29**	Fiesta	Ultra thin	**52**	Parachute	Tırtıklı (ribbed)
7	Dodo	Dotted ribbed form	**30**	Fitone	Classic	**53**	Playboy	Ultra thin
8	Dodo	Ultra thin form	**31**	Fitone	Big dotted	**54**	Playboy	Dotted
9	Durex	Extra sensetive	**32**	Fitone	Long duration	**55**	Playboy	Extra
10	Durex	Extreme	**33**	Fitone	Ribbed	**56**	Playboy	Ultra haz (ultra pleasure)
11	Durex	Intense	**34**	Fitone	Ultra thin	**57**	Preventivo	Moments
12	Durex	Feel thin	**35**	Let's	Klasik (classic)	**58**	Preventivo	Sensetive
13	Durex	Classic	**36**	Let's	Ekstra ince (ultra thin)	**59**	S- Box	Classic
14	Durex	Prolong	**37**	Let's	Geciktricili (retardant)	**60**	S-Box	Dotted type
15	Durex	Real feel	**38**	Let's	Kabartmalı (dotted)	**61**	S-Box	Strawberry
16	Durex	Air	**39**	Okey	Çifte haz (double pleasure)	**62**	S-Box	Ultra thin
17	Durex	Feel ultra thin	**40**	Okey	Ekstra zevk (extra pleasure)	**63**	Silky	Classic
18	Eros	Dotted type	**41**	Okey	Gerçek haz (real delight)	**64**	Silky Kiss	Aloe vera
19	Eros	Classic	**42**	Okey	Gerçek zevk (real pleasure)	**65**	Silky Kiss	Long love
20	Fe	Crowling	**43**	Okey	Nirvana hot	**66**	Silky Kiss	Love
21	Fe	Feel virgin	**44**	Okey	Rötar (retard)	**67**	Silky Kiss	Maximum
22	Fe	Classic	**45**	Okey	Sıcak temas (hot contact)	**68**	Extasia	
23	Fe	Long love	**46**	Okey	Sımsıkı (tight)	**69**	Mumu Safe	

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Table 2. List of lubricant gel samples

No	Lubricant brand	Type	No	Lubricant brand	Type	No	Lubricant brand	Type
1	OK	Nirvana	14	Noctis	Backside	27	Lick Me Sweetie	Apple
2	OK	Zero	15	V-Gold	Natural	28	Lick Me Sweetie	Watermelon
3	OK	Çilek (strawberry)	16	V-Gold	Strawberry	29	Lick Me Sweetie	Strawberry
4	Durex	Hisset (feel)	17	W-Fly	A+	30	Lick Me Sweetie	Anal - vaginal
5	Durex	Saucy strawberry	18	High Score	Chocolate	31	Fang Chung	Medical
6	Durex	Extreme gel	19	High Score	Natural	32	Fang Chung	Strawberry
7	Durex	Naturals pure	20	Viaxi	A+	33	Fang Chung	Chocalate
8	Durex	Play aloe vera	21	Viaxi	Chocolate	34	Cabs	Glide medical
9	Jelliaskin	Chocolate	22	Viaxi	Strawberry	35	Cabs	Best man medical
10	Jeliiaskin	Cherry	23	Viaxi	Glide	36	Maximum Sexual	
11	Joy Drops	Herbal	24	Lick Me Sweetie	Melon	37	Porcodile	Glide
12	Joy Drops	Natural	25	Lick Me Sweetie	Vanilla	38	Spanische Fliege	
13	Noctis	Natural	26	Lick Me Sweetie	Ginseng	39	Scream	Long time gel for men

Table 3. List of samples that can be used as lubricant

No	Brand	Type	No	Brand	Type
1	Komili	Riviera Olive oil	5	Johnson's Baby	Aloe Vera
2	Komili	Extra Virgin Olive oil	6	Petekoğlu	Beeswax
3	Vaseline	Petroleum jelly	7	Dalan d'Olive	Hand Cream
4	Handmade Olive oil		8	Nivea Soft	Body Cream

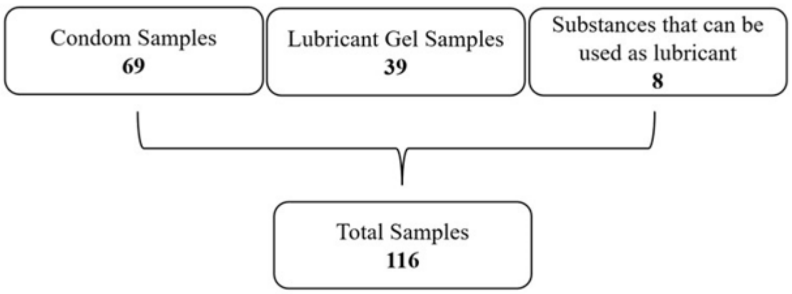

Figure 1. Total number of samples

ATR-FTIR Spectroscopy Analysis of Condoms and Lubricants

Agilent Cary 630 FTIR spectrometer was used in this study. For the analysis of lubricants that enable the characterization of condoms, the outer surfaces of the samples were placed in the sample analysis section of the device in a double layer. To prepare the lubricant samples and the product types that can be used instead of lubricant for analysis, a drop of 0.1 mL, precisely was dropped into the sample analysis section of the device with the help of a micropipette. The solid wax was grated with a small grater cleaned with 70% ethanol and the pieces were placed in the sample analysis section of the device. All condom and lubricant samples were analyzed in the wavelength number range between 650 cm^{-1} and 4000 cm^{-1} with a resolution of 4 cm^{-1}. For each sample, the device performed 16 sample scans at a time. Characteristic wavelength numbers of chemicals in lubricant samples are given in Table 4.

Table 4. Characteristic wavelength numbers of chemicals in lubricant

Lubricant Types	FTIR device specific wavelength numbers
PDMS	1400 cm^{-1} to 970 cm^{-1}; 1260 cm^{-1} antisymmetric CH3 deformation Si-O-Si bond stretching between 1090 cm^{-1} and 1020 cm^{-1}
PEG	3100 cm^{-1} to 3700 cm^{-1} O-H bond stretching 2872.02 cm^{-1} broad spectrum 1466 cm^{-1}, 1346 cm^{-1}, 1260 cm^{-1} and 1105 cm^{-1} small spectra
Glycerin	3100 cm^{-1} with a strong and specific O-H bond stretching at 3600 cm^{-1} 2939 cm^{-1} to 2885 cm^{-1} C-H bond stretching 2081 cm^{-1}, 1648 cm^{-1}, 1417 cm^{-1}, 1377 cm^{-1}, 1136 cm^{-1}, 1080 cm^{-1}, 1041 cm^{-1} and 992 cm^{-1} specific spectra

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Library Creation and Library Comparison

The wavelength numbers of the analyzed condoms and lubricants/substitutes were recorded, and 2 databases were created for condoms and lubricants each, separately. For library comparison, samples were randomly analyzed and compared with the relevant libraries and matching results were examined.

PCA (Principal Component Analysis)

PCA and cluster analysis were performed by using 1.2 version of SpectraGryph software and 3.32.0 version of Orange Data Mining software to compare and distribute the samples.

Results

ATR-FTIR Spectroscopy Analysis of Condoms and Lubricants Findings

A total of 47 different lubricant gels and lubricant-like products, as well as 69 different condom samples, were analyzed. The results indicated that 66 out of the 69 condom samples contained PDMS. A review of the literature revealed that condoms containing PEG and glycerin are significantly less common, with only three condom samples in this study found to contain glycerin (Figure 2). Notably, no condoms containing PEG were identified.

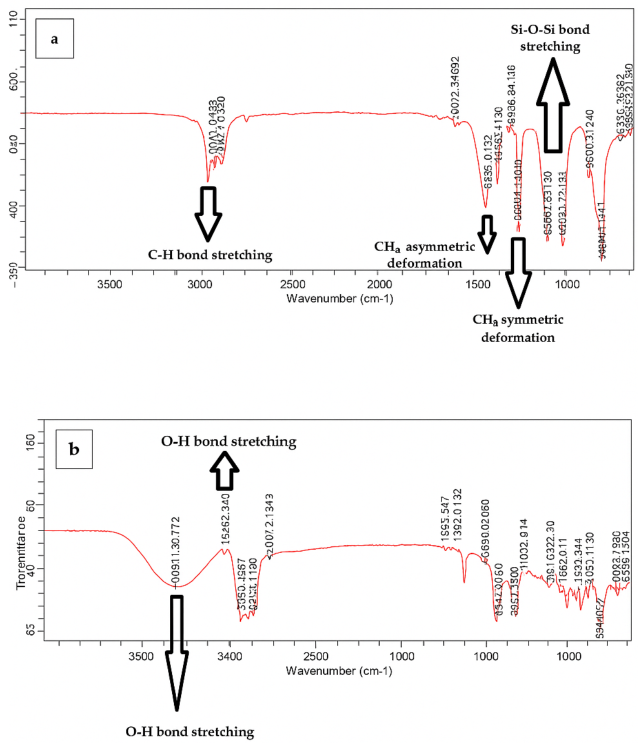

Figure 2. ATR-FTIR spectrum image of condom sample contains PDMS (**a**) and glycerin (**b**)

Additionally, while one lubricant gel was found to contain silicone-based PDMS , 38 lubricant gels contained water-based glycerin (Figure 3). Among the eight lubricant-like products analyzed, two were petroleum-based, three were oil-based, two contained water-based glycerin, and one had an organic composition.

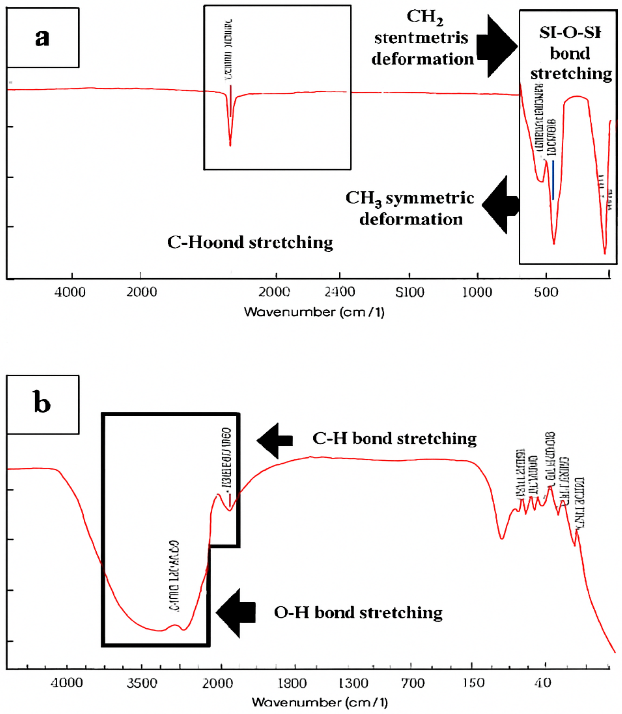

Figure 3. ATR-FTIR spectrum image of lubricant gel sample contains PDMS (**a**) and glycerin (**b**)

The chemical content percentages of all samples in the study as a result of ATR-FTIR analyses are shown in Figure 4.

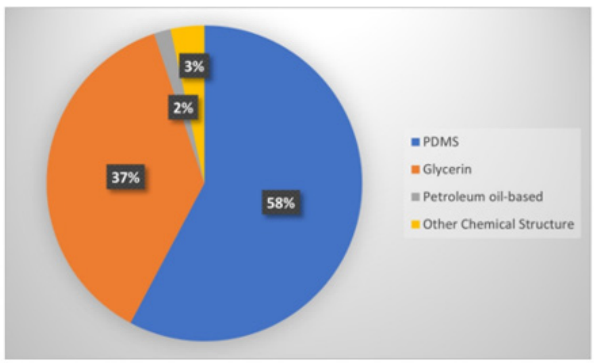

Figure 4. Chemical contents of all samples in the study by ATR-FTIR analyses

Library Creation and Library Comparison Findings

When condom samples were randomly scanned and compared within the newly developed database, glycerin-containing condoms were correctly matched with their reference data at a rate of 99.994%–99.997%. Similarly, condoms containing PDMS exhibited a match rate of 99.993%–99.997% (Figure 5). In the lubricant database, glycerin-containing samples were matched with an accuracy of 99.991%–99.998%, while silicone- and PDMS-containing samples exhibited a match rate of 99.989%. Petroleum-based lubricants demonstrated a matching accuracy of 99.995%–99.996%, confirming the reliability of the database for forensic comparisons (Figure 6).

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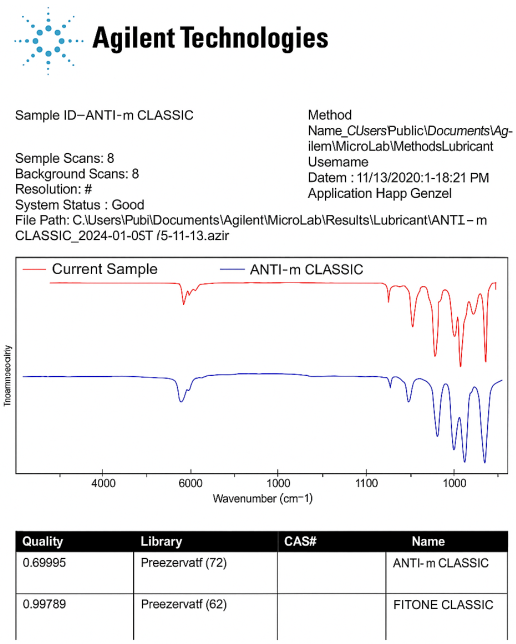

Figure 5. Library comparison result of a condom sample

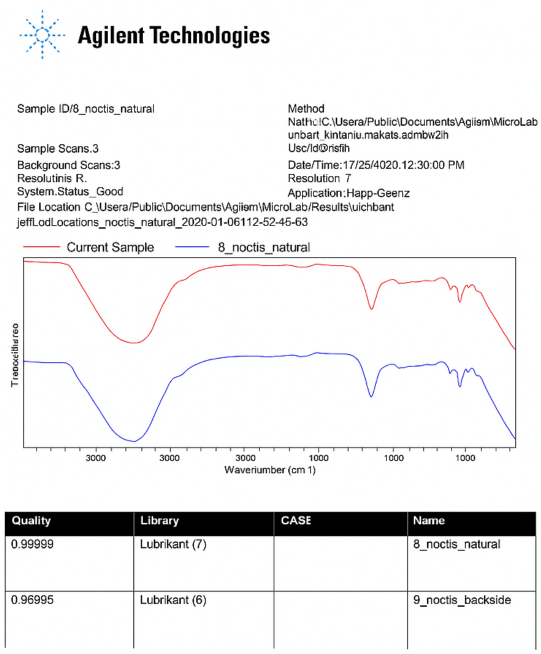

Figure 6. Library comparison result of a lubricant sample

PCA Findings

The Principal Component Analysis (PCA) conducted on lubricants revealed that the first two principal components (PC1 and PC2) explained 85% of the total variance, indicating that the majority of the variability in the dataset can be effectively represented by these two components. Additionally, K-Means clustering analysis was performed, and the highest clustering performance was observed at k=3 (C1, C2, C3). The Silhouette score for k=3 was (0,733), which was the highest among the tested cluster numbers. When these results are evaluated together, it is evident that the low-dimensional representation obtained through PCA effectively captures the natural groupings within the lubricant dataset and that dividing the dataset into three main clusters is statistically more meaningful (Figure 7).

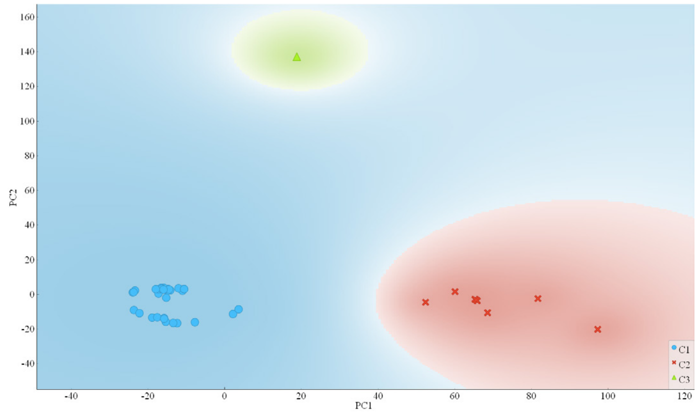

Figure 7. PCA and k-means results of lubricants

The Principal Component Analysis (PCA) performed on the condom dataset showed that the first two principal components (PC1 and PC2) accounted for 86% of the total variance, demonstrating that these two components capture most of the variability in the data. In addition, K-Means clustering was applied, and the optimal clustering solution was found with k=2 (C1 and C2), yielding a Silhouette score of 0.464. Together, these results suggest that the two principal components provide a robust representation of the underlying structure within the dataset, and dividing the data into two clusters offers a meaningful and statistically significant classification (Figure 8).

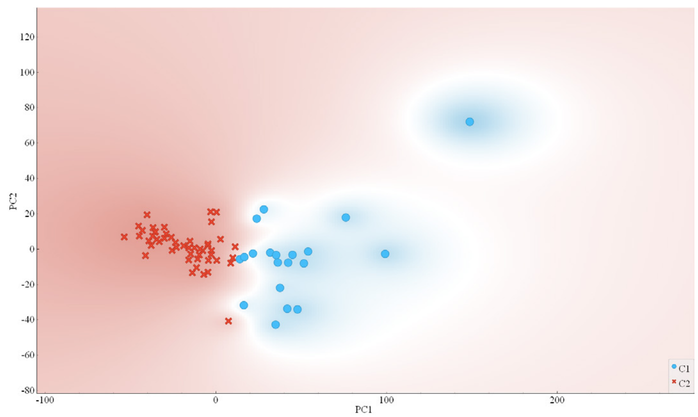

Figure 8. PCA and k-means results of condoms

Discussion

In this study; a total of 47 lubricant gels and 69 condom samples were analyzed to assess their chemical composition and forensic classification potential. Most condom samples (66 out of 69) contained PDMS, while glycerin was detected in only three samples, and none contained PEG. Among lubricants, one was silicone-based (PDMS), 38 were water-based with glycerin, and the remaining included petroleum-based, oil-based, or organic compositions.

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Establishing a database for forensic applications has proven to be highly effective in achieving reliable and successful outcomes. High matching accuracy was achieved using the developed reference database, with match rates exceeding 99.98% for all compound types. These successful matching results of the library comparison indicate that the identification of condom and lubricant samples found at the possible crime scene will benefit the investigation in order to identify the perpetrator.

Principal Component Analysis (PCA) and K-Means clustering confirmed that the datasets could be meaningfully represented in lower dimensions—two components explaining 85–86% of variance. Optimal cluster numbers were k=3 for lubricants (Silhouette score: 0.733) and k=2 for condoms (Silhouette score: 0.464), supporting the presence of natural groupings and the robustness of the analytical approach for forensic classification.

A review of the literature highlights a gap in lubricant analysis research, as most studies focus on condom lubricants rather than personal lubricants. Since condoms are commonly used in sexual assault cases, most research has concentrated on silicone-based lubricants. However, in cases where the offender does not use a condom or employs both condom and personal lubricants, the presence of lubricant residues becomes critical forensic evidence.

Burger et al. (2005) developed a method for generating electropherogram profiles for 66 of 68 lubricant products using capillary electrophoresis. By using PCA analysis 233 samples out of 263 were classified into their correct sample group. The researchers emphasized that this method required minimal sample preparation, did not involve organic solvents, and enabled analysis within approximately 20 minutes per sample. They concluded that capillary electrophoresis had potential forensic applications for differentiating condoms and personal lubricants, though it lacked full discriminatory capability [10].

Some studies aimed to improve the methods of analysing lubricants and condoms. For example; a study investigating the phenolic components of lubricant compositions performed a titration using the Karl Fischer method following IR spectrum analysis [11]. Two studies conducted in 2009 and 2011 examined a sample group of lubricant specimens in terms of their possible acid content and the extraction of lubricant oils using different methods [12,13].

The study by Moustafa and Bridge in 2017 has a similar basis to this research, but differs from our research in terms of creating a library. The reference study in question compared a lubricant with a personal hygiene product in sexual assault cases. However, although a statistical method such as PCA and LDA was used in the study, the instrumental analysis was performed with DART-TOFMS. In this context, this study can be interpreted as more successful in terms of obtaining faster and easier results [14].

In a review of the chemical analysis of condoms and lubricants in 2020, Burnier et al. compared various methods of analysis. It was revealed that the FTIR method can detect PDMS, PEG and nonoxynol-9. When applied to simulated cases, no interference between vaginal secretions and PDMS was reported and separation was achieved [6].

Another study conducted in 2021 focused on elucidating the structure of the condoms under investigation using GC-MS analysis . All 70 samples selected for GC-MS analysis contained silicone-based PDMS lubricants, lubricants such as PEG were not detected by GC-MS, the main analysis method of this study [15]. In another reference from 2021, although lubricants were subjected to IR analysis within a vaginal fluid-like matrix, only 7% of the analysis results were confirmed by GC-MS [15].

In another study; the PCA and classification results demonstrate how FTIR spectroscopy (using both ATR and DRIFTS techniques) and chemometric methods (PCA and HCA) can be applied to the forensic analysis of silicone-based condom lubricants. PCA explained 98% of the variance in ATR data and 86% in DRIFTS data, with both techniques effectively grouping different lubricants. However, a distinct separation between silicone-based condoms was not observed, suggesting that FTIR-DRIFTS analysis has limitations in distinguishing between different brands and models. The similarity of chemical profiles between real crime scene samples and reference materials further supports the potential of this method in forensic applications [16].

Thomas et al. (2022) investigated the environmental factors influencing the persistence and chemical composition of lubricants in condoms exposed to vaginal secretions. Using GC–MS, they examined the storage conditions of vaginal swab samples collected after sexual assault. The study primarily focused on PDMS- and PEG-based lubricants and found that PDMS residues could be detected in vaginal swab samples for up to 72 hours. Two different storage temperatures (+4°C and -20°C) were tested, and results indicated that room temperature was the most suitable condition for preserving condom traces in forensic investigations. Based on these findings, further studies employing FTIR spectroscopy—an effective method for lubricant analysis—are recommended to explore the impact of environmental factors on condom residue analysis [17].

A more recent study conducted by Nimi et al. in 2023 carried out the spectroscopic analysis of lubricants that could be used in sexual assault cases. Unlike this study, this research incorporated chemometrics in the statistical analysis phase [18]. In another recent study that simulated realistic scenarios, a group of lubricants was analyzed alongside various bodily fluids also in this study, the PCA analysis explained 98% of the variation in 25 condom samples using two components, forming three main groups: PDMS-based (G1), water-based (G2), and glycerin-based (G3) lubricants. A more detailed PCA for PDMS-based lubricants explained 97% of the variation, successfully classifying the samples. Some sample pairs were closely positioned due to spectral similarities. Classification analysis validated the grouping with a 99.6% DP, and the PCA model achieved 100% accuracy, precision, and specificity [19].

Studies in the literature predominantly focus on developing methods for analyzing condom and lubricant chemicals. While many of these works confirm the presence of components such as PEG, PDMS, or glycerin, they often lack quantitative detail. Notably, silicone-based PDMS is commonly observed, which is consistent with the findings of this study.

Although numerous studies utilizing IR spectroscopy exist for the analysis of lubricants and condoms, they generally emphasize either chemical characterization or compositional profiling, often focusing on only one type of material. There is a significant gap in the literature regarding the combined forensic analysis of both condoms and lubricants as potential evidence. This study aims to address this deficiency.

Furthermore, while some studies have employed statistical validation, most have not established spectral reference libraries. As a result, these studies are often limited to basic identification rather than supporting forensic comparison. In rare cases where libraries or comparative analyses exist, the methodologies typically involve complex and preparation-intensive instrumentation.

In contrast, this study offers a rapid, preparation-free, and statistically validated method for chemical component analysis. This approach not only enhances efficiency but also enables practical forensic applicability through the creation of a continuously expandable spectral library.

Conclusion

The successful matching results from this spectral library demonstrate its potential utility in forensic casework. It enables the identification of condom and lubricant residues recovered from crime scenes or biological samples (e.g., vaginal or anal swabs), supporting suspect profiling and contributing to case resolution. By enabling fast, effective, and comparative analysis, this study offers a valuable forensic tool for institutions in Türkiye and potentially beyond.

Conflict of Interests
The authors declare that there is no conflict of interest in the study.

Financial Disclosure
The authors declare that they have received no financial support for the study.

Ethical Approval
In this study, no experimental study was performed on humans or human samples and no ethics committee approval was required since only inanimate objects were used.

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