EUROPEAN JOURNAL OF BIOMEDICAL AND PHARMACEUTICAL SCIENCES
http://www.ejbps.com

ISSN 2349-8870
Coden USA: EJBPBO
Volume: 13
Issue: 4
Year: 2026

COMPARATIVE INSTRUMENTAL ANALYSIS FOR LIPSTICK COSMETIC EVIDENCE: A REVIEW

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DOI: https://doi.org/10.5281/zenodo.19413741

How to cite this Article: Ankita Mishra[1*], Anchal Dhiman[1], Shivali[2*], Himanshu Kondal[2], Dalbir Singh[3]. (2026). Comparative Instrumental Analysis For Lipstick Cosmetic Evidence: A Review. European Journal of Biomedical and Pharmaceutical Sciences, 13(4), 359–367.

Article Received on 05/03/2026 **Article Revised on 25/03/2026** **Article Published on 04/04/2026**

ABSTRACT

Cosmetic products are mainly used by women in their day-to-day activities, while lip cosmetics are used by both genders. Lip cosmetics have been useful in the investigation of law cases, as they tend to leave behind evidence on the body, clothing, cups, tissue papers, handkerchiefs, and on other surfaces during the commission of the crime. The evidence of lip cosmetics, when available, acts as useful evidence, which helps in establishing links between the victim, the suspect, and the crime scene. The evidence obtained from the lip cosmetics, based on the composition, is of great value in the investigation of sexual assault crime scenes. Several instrumental methods have been established for the investigation of the composition of lip cosmetic creams, which helps in the differentiation of lip cosmetic products. The investigation of lipstick helps in establishing links between the two lipsticks, which could be the same or different. The discrimination of lipsticks is of great importance in the investigation of crime scenes. This review article highlights the various analytical approaches used in the investigation of lip cosmetic creams, including thin layer chromatography, high-performance liquid chromatography, gas chromatography-mass spectrometry, ultraviolet spectroscopy, visible spectroscopy, Fourier transform infrared spectroscopy, Raman spectroscopy, and X-ray fluorescence.

KEYWORDS: Lipstick, Trace Evidence, Chromatography, Spectroscopic techniques.

INTRODUCTION

Smears of lipstick have been defined as a type of trace evidence that is commonly found at the crime scene, which can link a suspect to a crime or victim. They can be found on various surfaces, such as glasses, cigarette butts, clothing, tissues, or even skin. This type of evidence is considered to be quite informative, especially in criminal investigations related to sexual assault, murder, or even violence between individuals.[1,3] Various chromatographic and spectroscopic techniques have been used to determine the composition of such evidence related to lipstick, which can even distinguish between various types of evidence. This review is focused on providing information about various techniques that have been used to analyze evidence related to lipstick, including their importance.[4,7] The term "kosmeticos" originates from Greek word which means skilled in arranging or beautifying used for the cosmetics.[8]

Cosmetic is defined by the Federal Food, Drug, and Cosmetic Act (FD&C) as "Articles intended to be rubbed, poured, sprinkled, or sprayed on, introduced into, or otherwise applied to the human body for cleansing, beautifying, promoting attractiveness, or altering the appearance".[9] They are used by all ages, from infants to children to adults. It includes facial cream, moisturizing cream, body lotion, lip balm, lipstick, eyeliner, and nail polish. Out of all, the most commonly used cosmetic by women is lipstick which not only do they enhance the beauty of the lips, but they also help to moisturize them.[10,11]

TYPES OF LIP COSMETICS

Lipstick can be defined as the dispersion of coloring matter consisting of an appropriate mixture of oil, fat, and wax, with the addition of suitable proportions of perfuming and flavoring agents and having the consistency of a stick to provide significant gloss and coloring to the lips when applied. The different types of lipstick include moisturizing lipstick, satin and sheer lipstick, matte lipstick, cream lipstick, pearlescent and frosted lipstick, long-lasting/non-transfer lipstick, etc., are available in markets.[12]

Lip balms are used to moisturize and maintain the softness and health of the lips by protecting them from damage and helping to retain the natural moisture of the lips. It is made up of a mixture of waxes, oils, butters, and emollients. The waxes add smoothness to the lips, the oils add moisture, the butters add creaminess to the lip balms, and the emollients such as petroleum and lanolin add a fatty film to the lips that protects them from dryness. All the components of the lip balms act synergistically to improve the look of the lips. Most of the contemporary lip balms also contain sunscreen agents that protect the lips from damage by the ultraviolet rays of the sun, thus improving the look of the lips. Antioxidants such as vitamins C and E also act by reducing the damage done by free radicals to the cells.[12]

Lip gloss gives the lips a soft, shiny, and smooth look. It contains a high proportion of essential oil and relatively less proportion of wax and pigments than lipstick. Tocopherol or vitamin E helps to moisturize the lips and prevent dryness. Shea butter also helps in the moisturization of the lips. Polybutene gives the lips translucency by having a high refractive index and glass-like appearance.[12]

COMPOSITION OF LIPSTICK

The lipstick formulations are prepared by mixing different kinds of waxes, oils, pigments, dyes, preservatives, and other additives. Ingredients used in lipstick formulations are castor oil, paraffin wax, beeswax, beetroot powder, powder derived from ripe fruits, shikakai, lemon oil, orange essence, and vanilla essence. Lipsticks are made using different ingredients that are derived from both natural and artificial sources. Synthetic as well as herbal kinds of lipsticks are easily available. Herbal lipstick is gaining popularity because of the low degree of side effects. However, synthetic lipstick may have a higher degree of side effects. For example, metals such as nickel and copper that are used in lipstick formulations may cause an allergic reaction.[12,16]

Table 1: Material used in the formulation of lipstick.[12]

S. No.	Ingredients	Roles
1.	Bees wax	Thickening agents
2.	White soft paraffin	Base
3.	Olive oil	Moisturizing agent
4.	Pigment	Binder
5.	Acacia	Additive
6.	Orange juice	Antioxidant
7.	Vitamin E	Antioxidant
8.	Beetroot juice	Coloring agent
9.	Punica- grantum juice	Coloring agent

LIPSTICK AS EVIDENCE

In the field of forensic science, cosmetic smears are one of the forms of physical evidence that provide corroborative linkages between the suspect, victim, and scene of crime. In accordance with the principle of mutual exchange, cosmetic smears may be found on the victim and the suspect, as well as on objectssuch as cups, handkerchiefs, tissues, cigarette butts, and other surfaces that are involved in the execution of burglaries, rapes, and other forms of violence, and in any other case where women are involved.[1] Since such smears are not easily visible to the naked eye, they are usually not noticed during the commission of crime and may not be noticed by the criminals. Recognition of their source may provide a link between the suspect and the victim and the scene of crime. Cosmetics such as lipstick are synthesized using different chemicals such as pigments, organic compounds, and wax. Since different lipstick brands use different formulations of different chemicals, a link may be established between the evidentiary traces and the lipstick of the suspect. In general, lipstick is a mixture of different chemicals such as wax, oil, pigments, dyes, preservatives, and additives.[1,4,7,12]

INSTRUMENTAL ANALYSIS

Lipstick smears, previously considered insignificant in terms of evidence, have gained considerable importance owing to improvements in analytical techniques and technology. Various studies have been carried out in order to assess the potential of chromatography techniques in evaluating the quality, safety, and authenticity of lipsticks. Some studies compare branded lipsticks with local or counterfeit lipsticks in order to understand the differences. Various techniques are used for the analysis of lip smears, as depicted in Figure 1.[1,12]

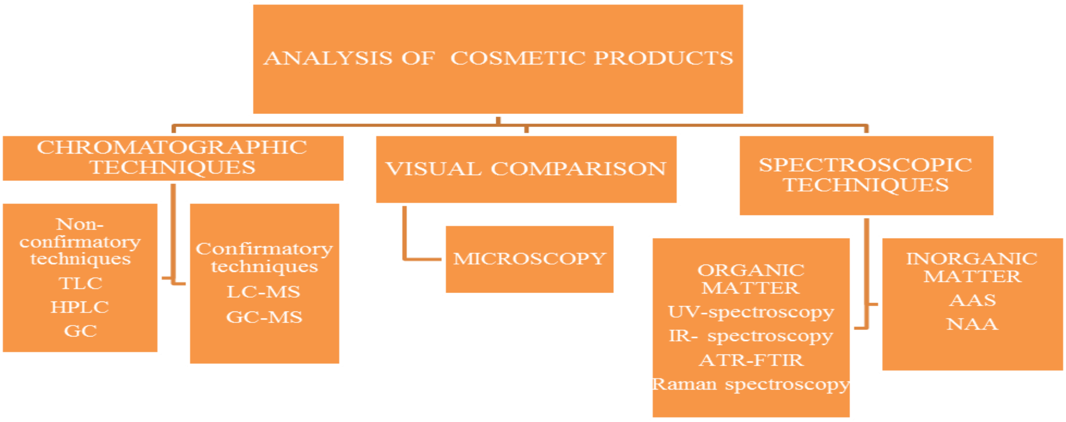

Figure 1: Showing various analytical techniques for examination lip cosmetics.

CHROMATOGRAPHIC ANALYSIS

1. **Thin-Layer Chromatography (TLC)**: It is a technique used to separate the components of a mixture by utilizing a thin stationary phase. The analytical and preparative purposes of chromatography are achieved by using TLC. The analytical scale of TLC is used to monitor the process of a chemical reaction, whereas the preparative scale of TLC is used to purify small amounts of chemical compounds. The technique of TLC is popular due to its simplicity, cost-effectiveness, sensitivity, and ability to rapidly separate mixtures. The principle of TLC is similar to the principle of other chromatography techniques. The chemical compounds used in TLC have specific affinities for the mobile phase and the stationary phase. The principle of TLC is based on the affinity of chemical compounds. The aim of TLC is to obtain well-separated spots.[19,22]

Advantages and Disadvantages: TLC is a simple and cost-effective chromatography technique. It is possible to separate more than one compound by using a single TLC plate. However, an appropriate mobile phase should be chosen for each compound. The solvent system of the TLC plate can easily be changed, and the use of more than one solvent to obtain TLC results is possible. The stationary phase of the TLC plate contains a short phase, and this may affect the separation of some compounds. In some cases, where the detection limit of the compound to be chromatographed is very low, other chromatography techniques may prove to be more suitable. The open nature of the TLC technique makes the process sensitive to changes in humidity and temperature.

High Performance Thin Layer Chromatography (HPTLC) is the latest version of the classical Thin Layer Chromatography technique. The sample is spotted on the surface of the stationary phase consisting of fine adsorbent particles (silica gel with 5 µm particle size) coated as a thin layer on a glass plate. The plate is then introduced into the development chamber and the solvent mixture ascends the plate by capillary action, causing the components of the mixture to get separated based on differential adsorption affinities. More polar compounds are retained strongly on the stationary phase and travel less distance on the plate (lower Rf values), whereas less polar compounds travel greater distances.[23,26]

ADVANTAGES[23,26]

- It can accommodate large numbers of samples (70+ tracks are possible on one plate) and only minimum volumes of solvent used.
- It offers high resolution and sensitivity.
- It can be used with different detection techniques like UV, fluorescence, or spray reagents.
- It offers permanent records with the possibility of accurate quantification using densitometers.

DISADVANTAGES[23,26]]

- It may cause overlap of components in very complex mixtures and accommodate only non-volatile compounds.
- It can be less accurate if manual operations are involved.
- It is very expensive initially and labor-intensive as the plates are one-time usage items.

2. **High Performance Liquid Chromatography (HPLC)**: It is one of the most powerful and commonly used techniques in the field of analytical chemistry today, used for the separation, identification, and quantification of the individual components of a given mixture. The technique works on the principle of passing a liquid sample, known as the mobile phase, which is usually water, acetonitrile, methanol, etc., through a narrow column filled with fine particles, generally of 1.7–5 µm size, under high pressure, usually between 200–1500 bar. The stationary phase of the column is the surface that is responsible for the separation of the individual components of the sample, with the non-polar molecules showing a stronger affinity towards the stationary phase, hence taking longer times to

elute, while the polar molecules tend to elute quickly.[27,30]

Advantages of HPLC[27,30]

- HPLC facilitates the high-resolution separation of complex mixtures of proteins, effectively distinguishing proteins that show little difference in their structure. This helps in detecting impurities in the samples and determines the purity of the samples. Also, the high sensitivity of HPLC helps in detecting the amount of proteins present in the samples, ensuring the accuracy of the results.
- Compared to the traditional methods of analyzing proteins, HPLC facilitates quicker analysis and the simultaneous analysis of several samples in a short time.
- The variety of separation techniques in HPLC makes it applicable to the analysis of various proteins. It helps in the analysis of both hydrophobic membrane proteins as well as highly polar water-soluble proteins.

Disadvantages of HPLC[27,30]

- The cost of the equipment required for HPLC analysis is quite high, and the additional costs of maintenance also contribute to the high costs incurred in the operation of HPLC.
- The complexity of the HPLC analysis process makes it necessary to possess high technical skill to operate the HPLC efficiently.

3. GC (Gas Chromatography) is the basic separation technique using a gas mobile phase (like helium) and heat to vaporize and carry volatile/semi-volatile compounds through a column. It separates based on boiling point and polarity. Detection can be simple (e.g., FID flame ionization detector) or advanced, but GC alone doesn't give molecular identification — just retention times.[31,33]

GC-MS: It is a combined technique, comprises gas chromatography as the separation tool and mass spectrometry as the detector. In GC-MS, the mixture under investigation is subjected to vaporization and then injected into the gas chromatograph, in which separation of the components of the mixture takes place in the gaseous phase in accordance with their interaction with the stationary phase of the gas chromatograph and their boiling points. Once the separation is complete, the components are subjected to ionization, with electron impact being the commonly used method for this purpose, owing to its reliability.

GC-MS is particularly useful for the separation of mixtures that comprise volatile, thermally stable, and non-polar compounds. This technique can be used for the separation of a wide variety of mixtures, such as pesticides, volatile organic compounds, drugs of abuse, hydrocarbons, and essential oils, among others.

This technique has a number of advantages over other techniques, such as increased sensitivity, availability of a wide library of spectra for easier identification, and relatively lowers operational costs.[34,35]

LC-MS, chromatography is an extension of the HPLC technique but with the addition of MS. The separation is carried out using a liquid mobile phase that is a mixture of water and organic solvents such as acetonitrile without the application of heat or vaporization during the separation process. The technique is particularly useful for non-volatile, polar, ionic, heat-sensitive, or large molecular weight compounds such as pharmaceuticals, peptides, proteins, metabolites, and polar pollutants. The ionization is soft, usually through electrospray ionization or atmospheric pressure chemical ionization. As a result, more molecular information is available. Often, tandem MS is used.[34,35]

Table 2: Comparative studies of researchers on various cosmetic products.[36,51]

S. No.	Aim	No. of samples	Technique/Method	Results	References
1.	Examination of small quantity of lipsticks	100 samples of lipstick smear	Thin-layer chromatography and UV light source	Spots viewed under UV light give no outcomes, while developed plates revealed no. of spots	Barker and Clarke, 1972
2.	Forensic analysis of lipstick	117 lipstick samples	TLC, HPLC and energy-dispersive x-ray analysis using scanning electron microscope fitted with PGT- 1000 x-ray analyzer	Analysis of stains with dispersive x-rays did not interfere in analysis and comparison can be done with pure lipstick samples	Andrasko, 1981
3.	Comparison of lipstick by HPLC and investigate the effect of wear time and subject on the chromatogram	12 lipstick samples from various brands	A waters associate ALC 202/401 equipped with 660 solvent programmer and U6K universal injector was used for HPLC	Chromatogram of the wear time effect for Cover Girl samples could not be compared to pure sample, Avon samples for preliminary identification, and Aziza chromatogram	Reuland and Trinler, 1984

				easily compared and identified.	
4.	Analysis of lipstick	304 lipstick samples	Thin-layer chromatography and gas chromatography	Samples easily compared and GC might help in differentiating lipstick even with single manufacturer	Russell and Welch, 1984
5.	Spectroscopic detection of health hazardous contaminants in lipstick using laser induced breakdown spectroscopy	Four different type of lipstick	Laser induced breakdown spectroscopy (LIBS)	Lead, chromium and cadmium were present In every sample	Gondal et al, 2010
6.	Forensic discrimination of lipsticks by thin Layer chromatography and Gas chromatography-mass spectrometry	53 lipstick sample from 15 different manufacturers	Thin- layer chromatography and gas chromatography-mass spectrometry	Thin-layer chromatography is good screening technique during initial investigation and GC-MS servers as confirmatory technique it enables discrimination based on chemical structures of samples	Abdullah et al, 2011
7.	To identify the concentration level of various pigment and to determine suitable solvent system for different samples using TLC	30 lipstick samples of different brands were analyzed out of which 6 from Revlon brand and 6 from local brands	Thin- layer chromatography	Revlon lipsticks were best separated in toluene/benzene solvent system whereas local brand lipsticks were best separated in the toluene/acetone solvent system. when spots observed under UV light, local brands had more dark spots than Revlon	Srivastava et al, 2012
8.	To compare red pigments in different lipsticks by TLC	-----	Thin-layer chromatography	No precise difference was observed in HR_fvalue of both local and branded lipsticks	Joshi et al, 2013
9.	To examine lipstick by the various physio- chemical and instrumental method	17 different lipstick samples out of which 11 from popular brands and 6 from locals brands	Thin-layer chromatography, paper chromatography and photo calorimeter method	Paper chromatography was most effective method, and new solvent system produced best result for TLC and paper chromatography	Singh et al, 2015
10.	Differentiation of red lipsticks using the attenuated total reflection technique supported by two chemometric methods	38 red lipstick sample of 20 different manufacturers having same hue	Thermo Nicolet Is50 FTIR having orbit micro-ATR accessory, Thermo electron's OMNIC 9 software for obtaining spectra and statistic 12.5PL software and OriginPro 2017 software for statistical analysis	PCA and CA were helpful in providing preliminary information and correlation coefficient was best way in distinguishing lipstick samples	Gladysz et al, 2017
11.	To discriminate lipstick smears using ATR-FTIR and chemometrics	12 red lipstick samples from both local and foreign brands	Bruker tensor 27 FTIR spectrometer and two chemometric methods-principal component analysis (PCA) and hierarchical cluster analysis (HCA)	PCA and HCA successfully discriminated the lipstick samples into 6 distinctive clusters according to their brands. Chemometric methods gave more objective	Ghazali et al, 2018

				outcome compared to direct visual examination of FTIR spectra alone	
12.	To discriminate lipstick using visible and ATR-FTIR spectroscopy	40 samples of red color and nude shades of lipstick from 20 different brands	Cary 4000 UV- Vis double beam spectrometer and Nicolet iS50 FTIR spectrometer with diamond crystal	PCA and LDA provide 100% accurate classification results for red lipstick samples but misclassification would occur with nude colors.	Wong et al., 2019
13.	Comparative forensic analysis of lipsticks using TLC and GC	8 lipstick samples including both native and foreign brands	TLC and GC-FID were used	TLC provided more consistent results over a four-week period than GC-FID However neither TLC nor GC-FID could identify lipstick evidence obtained from circumstantial crime scenes.	Ezegbogu and Osadolor, 2019
14.	To classify lipstick with the help of ATR-FTIR spectroscopy	53 lipstick samples of red, pink and brown from five different brands (Blue heaven, Camiea, Premier, Elle 18 and Marlin)	Bruker FTIR spectrometer with OPUS version 7.2 software and chemometric methods such as PCA and LDA	LDA classify 100% sample accurately. 93.61% brown lipstick, 80.7% pink lipstick and 82.27% red lipstick were classified with PCA	Kaur et al., 2020
15.	To study the elemental profile of lipstick by AAS-health risk investigation	27 lipsticks from 9 different manufacturers having 3 different shades	AA-7000, Shimadzu AAS	Cadmium, lead, zinc, iron and copper were found in present in low concentration in lipsticks, but in two samples lead concentration that were above the acceptable limits	Chophi et al., 2021
16.	Discrimination of pink lipsticks using FTIR and Raman spectroscopy	20 distinct pink lipstick samples from MAC brands	Bruker VERTEX 70V vacuum FTIR spectrometer with Opus software (7.5) and BrukerSenterra confocal Raman microscope	Combination of vacuum FTIR and Raman produced reliable results for lipstick differentiation of up to 95.8% across all samples	Alblooshi et al., 2024

CONCLUSION

Recent studies recognize lipstick as one of the common items used by women belonging to different age groups, thereby effectively bridging the gap on various cultural, socio-economic, and age-related criteria (Gładysz et al., 2021). Lipstick has been traditionally recognized as a significant item, but it has been established as significant in various investigative scenarios as trace evidence (Gładysz et al., 2021; Sharma et al., 2019). Lipstick impressions are corroborative evidence that is frequently found at crime scenes involving physical assault, sexual assault, theft, burglary, and homicide (Andrasko, 1981; Gładysz et al., 2022). Lipstick impressions are normally found on surfaces that come into contact with the victim's or suspect's lips. These surfaces include the suspect's or victim's skin, handkerchiefs, cigarette butts, drinking glasses, tissues, etc. (Abdullaha et al., n.d.; Turkay& Kizil, 2024). The transferability of lipstick is due to its waxy, oily, and pigmented properties, thereby confirming lipstick as significant contact evidence that can effectively connect the suspect, victim, and crime scene (Gładysz et al., 2021). As highlighted in this review, lipstick is not just significant because it is found at crime scenes but is also significant because it can be chemically characterized, as highlighted in various studies (Sharma et al., 2019; Gładysz et al., 2022).

The framework of analysis of lipstick traces has developed significantly over the years, with many researchers using different discriminative approaches based on different underlying principles, sensitivities, and requirements (Gładysz et al., 2021). All approaches have agreed on the importance of using chromatography. In the foundational study on lipstick traces, Andrasko (1981) established the potential of using a combination of thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) with scanning electron microscopy (SEM) and X-ray analysis. In the study, extracts of lipstick stains were analyzed using both separation and direct analysis of the lipstick stains using SEM and X-ray. From the study, it was established that using such an approach, it is possible to differentiate all 117 lipstick traces. This is because, using HPLC, it is possible to separate and identify pigments such as eosin, carmine, and synthetic dyes. In addition, using TLC, it is possible to compare the Rf values of such pigments. This shows that it is possible to identify subtle differences in lipstick traces, even where their appearance is almost identical.

On this basis, modern developments in chromatography have resulted in the application of gas chromatography–mass spectrometry (GC–MS) and high-performance thin layer chromatography (HPTLC). Comparative studies that compare the effectiveness of thin layer chromatography (TLC) with that of GC–flame ionization detection (GC-FID) in the analysis of lipstick smears collected from tea cups following environmental exposure for as long as four weeks reveal that the n-alkane mixtures, as well as the volatiles, persist, thus allowing differentiation at the brand and batch level even after prolonged exposure (Abdullaha et al., n.d.). The application of HPTLC, which is distinguished by the finer layer thickness of the stationary phase, as well as the automated application of the samples, is effective in the analysis of nanogram quantities of herbal/organic-based lipstick formulations commonly found in the market in India. This modality is effective in the simultaneous analysis of multiple samples in a single run, thus making it effective in the analysis of evidence collected in sexual assault cases, especially when multiple cigarette butts or glassware are collected at the scene of the crime, as discussed in the study by Gładysz et al. (2021).

Significantly, spectroscopic methods, particularly non-destructive methods, have shown great promise for forensic lipstick analysis. Gładysz et al. (2017) used ATR-FTIR and chemo-metrics for the classification of red lipstick colors that were difficult to differentiate. The effectiveness of this approach was shown through the classification of red lipstick colors using vibrational modes of waxes, oils, and pigments. The study showed that the application of chemometrics was highly effective for the classification of red lipstick colors.

The vibrational modes of red lipstick were characterized by bands near 2900 cm^{-1} for C-H stretching and near 1740 cm^{-1} for C=O stretching. Factors such as wear, storage, fabric contact, oils from human skin, and humid environments were considered. However, an increase of over 90% was seen for discrimination when chemometrics were used. The work of Gładysz et al. (2017) and Gładysz et al. (2022) showed that using more than one approach was more beneficial. Raman spectroscopy has also shown great promise for forensic applications. This is because of the non-destructive and portable nature of Raman spectroscopy. The ability of Raman spectroscopy to analyze through an evidence-containing container was shown by Gardner et al. (2013). The ability of Raman spectroscopy to differentiate pink and red lipstick from the same manufacturer was shown. The ability of Raman spectroscopy was shown for 95% of these lipsticks using 532 nm or 780 nm laser lines. The practical application of this approach was shown for burglary investigations. This is because traces must be left untouched on glass or window sills.

Combining both LC-MS and GC-MS techniques provide better specificity through molecular identification. The GC-MS technique is found to be highly effective in analyzing conventional stick-type lipsticks that contain volatile waxes and fragrances. On the other hand, the LC-MS technique is found to be more appropriate for analyzing modern lipsticks that are available in liquid or matte forms and contain water-soluble dyes and preservatives (Gładysz et al., 2022). An analytical protocol that combines ATR FTIR, Raman Spectroscopy, and Ultrasound-Assisted GC/MS Extraction has been reported by Gładysz et al. (2022), wherein near-complete discrimination is achieved between visually identical shades of red lipstick by combining spectral information with fatty acid/fatty ester MS spectral libraries. The effectiveness of various techniques varies significantly. Chromatography techniques such as HPLC, HPTLC, and GC-MS are found to be highly effective in analyzing lipstick formulations, detecting traces of impurities, and identifying manufacturer-specific additives. On the other hand, vibrational spectroscopic techniques such as FTIR and Raman Spectroscopy are found to be proficient in generating complete molecular fingerprints quickly but are prone to degradation, especially when analyzing formulations that are highly similar in composition (Gładysz et al., 2021; Sharma et al., 2019).

The diversity in analytical techniques poses both a problem and an advantage. Sexual assault cases involving lipstick residue on clothing or human tissue, HPLC analysis may reveal the presence of a specific azo compound not found in the suspect's lipstick, while Raman spectroscopy can be used to non-destructively validate the compound's presence on fabric without sample loss (Gardner et al., 2013). Environmental influences such as exposure to sunlight, perspiration-induced changes in lipid composition, and interactions with surfaces (porous or non-porous) also play a role, as seen in recent studies on lipstick residue longevity under various storage conditions (Turkay & Kizil, 2024). Nevertheless, when collectively employed, lipstick analysis has been transformed from a corroborative tool to a powerful investigative tool that can conclusively incriminate a suspect with statistical certainty (Gładysz et al., 2022).

However, despite all these improvements, there is still much to be desired. While destructive techniques such as solvent extraction followed by HPLC or GC-MS analysis consume limited quantities of trace evidence, non-destructive techniques such as Raman spectroscopy may not be sufficiently sensitive to ultra-thin residue or heavily contaminated samples (Gładysz et al., 2021). Lipstick colors such as red are difficult to analyze owing to similarities in chemical composition, and standardization is lacking worldwide. Nevertheless, with the advent of chemometrics, portable instrumentation, and artificial intelligence-based spectral matching algorithms, we are on the cusp of a new era wherein lipstick analysis on-site is feasible (Sharma et al., 2019).

In conclusion, lipstick analysis is a testament to the adage that ordinary objects carry extraordinary investigative power. From sexual assault cases wherein a victim's collar bears a lipstick smear that incriminates a suspect to burglary cases wherein a lipstick stain on a wine glass in a victim's home incriminates a suspect, all analytical techniques reviewed herein—from classical chromatography to advanced spectroscopy—have collectively demonstrated that a single technique is not sufficient to produce reliable, admissible evidence (Andrasko, 1981; Gładysz et al., 2022). As cosmetic formulations evolve with new pigments, nanoparticles, and organic alternatives, continued research into hybrid, non-destructive, and environmentally resilient protocols will ensure lipstick remains a reliable ally in the pursuit of justice. Ultimately, this review affirms that what adorns the lips of millions can, in the hands of forensic scientists, unmask the truth behind countless crimes, reinforcing the enduring value of trace evidence in modern criminalistics.

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