A Standardized Analytical Framework for Perfume and Deodorant Trace Evidence in Forensic Science

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Abstract:

Fragrance traces on perfumes and deodorants are becoming a recognised and yet not extensively studied types of chemical trace evidence in forensic science. These products have varying blends of volatile and semi-volatile products, including alcohols, esters, aldehydes, fixatives, and additives, which may last long on surfaces to facilitate any association between people, objects and environments. Despite the fact that different analytical tools have been applied in the analysis of such residues, the lack of a uniform methodological framework constrains their dependability and interpretation measures. This review synthesizes and assesses existing instrumental methods, such as Gas Chromatography-Mass Spectrometry (GC-MS), Headspace Solid-Phase Microextraction (HS-SPME) as well as fourier Transform Infrared Spectroscopy (FTIR), based on their sensitivities and their ability to detect traces at the trace level. Persistence and transfer studies also find their way in the synthesis of the findings to explain the behavior of the fragrance compounds on various substrates and the effect of various environmental conditions. Upon this evaluation, this paper will present an analytical framework that is structured to enhance consistency, comparability, and evidentiary strength of the analysis of trace evidence of perfume and deodorants in the context of the forensic profession. Introduction Forensic chemistry, also called fragrance analysis, involves the analysis of perfume, deodorant, volatile organic compounds (VOCs) and analyzing the transfer of these substances onto different surfaces. Forensic chemistry is closely connected with fragrance analysis, perfume analysis, and crime scene analysis.

Key words: Forensic chemistry, perfume residues, deodorant traces, volatile organic compounds (VOCs), GC–MS, HS–SPME, FTIR, persistence analysis, transfer mechanisms.

1. Introduction

Using perfume and deodorant residues has been a notable area of concern among trace evidence in the area of forensics because the elements generate some form of associative association between the individuals, property, and the crime location. They are the complex mixtures of volatile organic compounds (VOCs), solvents, fixatives, and additives, which constitute distinct chemical signatures that can be identified and compared through the assistance of the contemporary analytical techniques [1]. Previously, the fragrances were more treated as the indicators of sense and were not considered suitable in the occurrence of forensic interpretation. However, the components in fragrances at traces have now been identified and profiled due to the advancement in analytical chemistry (in particular, the creation of strong chromatographic and spectroscopic methods) [2]. The similarity of both formulations is the presence of natural and synthetic substances in the compositions, and the features of chromatographic and spectroscopic patterns are distinctive. It is this individuality that makes it possible to distinguish one product against another and to relate recovered residues to some brand or formula. It has been shown that depending on exposure to the environment, the nature of the substrate and the volatility of the fragrance compound, fragrance compounds may persist over several hours or days, on textile fiber, skin, paper and metallic objects [3], [4]. The persistence has good opportunities in the arena of forensic reconstruction

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techniques can also be employed to determine functional groups in complicated mixtures without destroying the samples and in a non-destructive manner: Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy [7]. A combination of these methods provides a strong qualitative and quantitative study, which assists in exploring the residues of perfumes and deodorants. Regardless of all these advances, there is no standardized set of protocols of sampling, detection and analysis in the discipline. The discrepancies in laboratory procedures, sensitivity of analysis, and documentation of the findings is still to influence the reproducibility and the reliability of evidence fragrance analysis [8]. These problems justify the need to have a structured and substantiated analytical model that would standardize the existing procedures and would lead to their uniformity in the forensic laboratories. The current review satisfies this requirement and summarizes the existing literature base on the chemistry of the fragrances, the ways of their detection, persistence behaviour, and the mechanisms of their transfer. It implies a standardized approach to the interpretation involving both the instrumental approach and chemometrical techniques that increase the forensic value of perfume and deodorant remains.

2. Review of Literature

2.1 The History of Fragrance Analysis in the Forensic Sciences

The scientific examination of the traces of perfume and deodorants as the evidence of a crime began gaining momentum in the late 20 th century, at which point the scientists first took an interest in the chemical diversity of commercial perfumes. Primary examination revealed that perfumes and deodorants also contain a significant amount of volatile and semi-volatile compounds comprising of esters, alcohols, aldehydes, and terpenes among others which generate chemical signatures of the products [7]. At the time, the strength of the analysis was not high but with the emergence of Gas Chromatography Mass Spectrometry (GC-MS), it was much simpler to determine the compounds and even the researcher was capable of examining the remaining residues much more easily at traces of concentration [8]. These were the first steps towards the analysis of fragrances that is more advanced, which is being utilized now.

2.2 New Developments in Analytical Detection Procedures

The realization of the 2000s witnessed the further development of the sphere of fragrance detection within the context of the forensic environment, because the extraction and sampling technique were improved. Headspace Solid-Phase Microextraction (HS-SPME) was one method that was made very popular because of the absence of solvents, low probability of contamination, and high VOCs recovery off fabrics/skin and other surfaces [9]. At this stage, HS-SPME with GC-MS will be the most sensitive assay to detect the critical fragrance indicators of the formula such as linalool, limonene, benzyl acetate and others that dominate most of the contemporary formulae [10]. Liquid chromatography was increasingly employed by researchers using the Liquid chromatography, Tandem Mass spectrometry (LC-MS / ms) to determine semi volatile compounds that are less vulnerable to the GC based technique. The method is particularly practical in establishing the presence of non-volatile fixatives, phthalates, antioxidants and synthetic musks which fail to disappear off-surfaces after the light VOCs have been lost [11]. In addition to this, spectroscopic techniques also involve fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy have been applicable in the non-destructive quick screening of functional groups in complex fragrance mixtures [12]. The most recent developments involve the use of electronic-nose (E-nose) systems along with machine-learning algorithms that can also categorize smell patterns in addition to distinguishing between brands at high level of accuracy, especially when the system is applied in the field where a laboratory equipment may not be available [13].

2.3 Balancing and Stability of Fragrance Residues.

One significant portion of literature is devoted to the time taken by the perfume and deodorant residues which are visible upon being deposited. They are always shown to be stable on porous substances like cotton and wool more than smooth surfaces like metal and glass since they contain more adsorption capacity [14]. The environmental factors too are crucial; e.g. high temperature and ultraviolet light augment volatilization and oxidative alteration of most of the fragrance constituents [15]. Kinetic modelling has revealed that the light VOCs could be expected to degrade after a few hours whereas the heavier fixatives and synthetic stabilizers could hold up to 4872 hours or even longer depending on humidity and type of substrate [16]. The results help the forensic examiners to identify the meaning of the identified residues on the view that they were caused by a recent contact or secondary delay transfer.

2.4 Mechanisms of transfer and Casework relevancy.

The fragrance residues may have direct or indirect contacts. Primary transfer is when a fragranced individual touches a surface and the secondary can be by way of contaminated clothing or intermediate objects. It is experimentally known that quantifiable amounts of VOC can be moved within seconds of contact and its rate is also determined by pressure, friction, surface porosity among other factors and the volatility of the substance [17]. This finding is again supported by other studies done on adsorption behaviour and surface interactions that indicate that textiles are more likely to store transferred fragrances compared to smooth materials [18]. Such evidence on the use of fragrances is evident in casework reports. Chemical profile of the residues left behind by a suspect on clothing and other items matched the same as those left behind on victims or found at the crime scene, which provided useful associative evidence in some of the attacks, burglary and sexual-offense cases where no DNA or fingerprints existed [19].

2.5 Chemometric and Statistical Methods

Since the fragrance combinations normally incorporate a large pool of components that overlap, researchers begin to employ chemometric instruments to support objective comparison. The Principal Component Analysis (PCA) helps to classify the samples of the chromatograph by reducing the dimension and highlighting the chemical pattern shared by the samples [20]. The other method, which is used to group the samples in a manner similar to the similarity measures, is referred to as Hierarchical Cluster Analysis (HCA); this is a graphical method of the evaluation of connections between the fragrance profiles. Machine-learning methods such as Support Vector Machines (SVMs) and Artificial Neural Networks (ANNs) are potentially useful in automated fragrance formula identification and brand classification on VOC pattern [21]. These computation methods are more dependable in the area of interpretation, however they have the necessity of calling on standard data and tested methods of analysis so as to reproducibility.

2.6 Identified Research Gaps

Despite the fact the study of fragrance residues has gained popularity in the science community, there are major flaws associated with the technique. The first one is that there are no international standards of protocols regarding the formation, storage and analytical examination on fragrance remnants. Changing the laboratory protocols, equipment, and report criteria continue to influence the inter-laboratory reproducibility [22]. The environmental conditions such as airflow, humidity which is variable and real life exposure conditions have not undergone in-depth study although their linkage with persistence and transfer outcomes is remarkably high [23]. Another huge loophole is the lack of central and validated databases of chromatographic or spectroscopic profiles of commercial perfume and deodorant formulations. The lack of such reference collections makes comparative analysis challenging too as it is largely dependent on the samples of products that are available locally [24]. Also, probabilistic thresholds and likelihood-based interpretation models are not given in most researches making it a puzzle as to how far one can make an evidentiary match to reference material [25].

3. Methodology

3.1 Study Design

The current review was done in accordance with the Preferred Reporting Items on Systematic Reviews and Meta-Analyses (PRISMA). The framework was chosen since it provides a transparent and structured method of identifying, screening, and synthesizing scientific literature across different fields. Since publications pertaining to the topic of perfume and deodorant residues are found within the realms of forensic chemistry, analytical science, and environmental research, the application of PRISMA served the purpose of ensuring the selection process was unified and reduced subjectivity during the inclusion process [26].

3.2 Search Strategy

An extensive literature search was conducted through the large scientific databases, such as Scopus, Web of Science, PubMed, and ScienceDirect. Articles that were published between the year 2000 and 2025 were taken in order to reflect the developments in modern instrumental analysis and the latest forensic application. Relevant publications were searched with the help of a Boolean query: (perfume or fragrance or deodorant) and (trace evidence or volatile organic compounds or VOCs) and (forensic or persistence or transfer or detection). Reference lists of published articles with the key articles were manually verified to rule out missing influential studies, and reference management software was used to exclude any possible duplicates. This multi-step approach guaranteed a wide but narrow-focused searching of literature on the topic of examining fragrance residue [27].

3.3 Eligibility Criteria

There were definite inclusion and exclusion criteria to ensure a homogeneous and objective selection process:

Inclusion criteria:

- Research on perfume, deodorant or fragrance impressions in a forensic or analytical scene.
- Study with methods like GC -MS, HS-SPME, LC -MS/MS, FTIR or Raman spectroscopy.
- The articles that report data on detection sensitivity, persistence behaviour, transfer mechanisms or comparative profiling.

Exclusion criteria:

- The research was limited to cosmetic marketing or consumer preference.
- Articles that are not methodologically detailed or not quantitative.
- Published works that are not in full text.
- Multiplicity of databases [28].

These criteria were used to ensure that only methodologically good and scientifically relevant articles were included in the review.

3.4 Screening and Selection Process

The screening had been conducted in two phases. To reduce the obviously irrelevant studies, titles and abstracts were reviewed. The rest of the articles were screened with full-text review to identify the quality of methodology and relevance. Any doubt in the process of screening was sorted out by mutual discussion to ensure consistency.

Among the initially retrieved articles, 85 articles were duplicated. After the screening of the abstracts, 142 articles were eligible to be evaluated in terms of full-text. Finally, 68 articles that met all the eligibility criteria were used in the final synthesis.

Table 1 shows a summary of this process, which can be associated with the PRISMA-based selection flow.

<table>
<tr><th>Stage</th><th>Description</th><th>Number of Records</th></tr>
<tr><td>Identification</td><td>Total records retrieved</td><td rowspan="2">412</td></tr>
<tr><td>Duplicates removed</td><td>85</td></tr>
<tr><td>Screening</td><td>Titles/Abstracts</td><td>327</td></tr>
</table>

	evaluated	
Excluded (irrelevant)	185	
Eligibility	Full texts assessed	142
Excluded (methodology inadequate)	74	
Inclusion	Studies included in final review	68

Table 1 — PRISMA Study Selection Summary

3.4 Data Extraction and Quality Assessment

The important information was systematically obtained regarding each chosen article, with the type of product under study (perfume or deodorant), the substrates under study (textiles, skin, metal, or paper), and the methods applied. The additional information about such parameters as persistence time, degradation behaviour and transfer characteristics were also reported. The Critical Appraisal Skills Programme (CASP) checklist was used to determine the reliability of the included studies. This instrument considers variables like validity, methodological transparency, and reproducibility [29]. The indicators analytical performance such as limit of detection (LOD), accuracy, and precision and repeatability were contrasted with the international standards suggested by the European Network of Forensic Science Institutes (ENFSI) and the ASTM standards [30].

3.5 Data Synthesis

The information that was extracted was arranged in three main thematic areas:

- **Detection techniques:** Evaluation of chromatographic, spectroscopic and sensor-based methods of analyzing fragrance residues.
- **Persistence characteristics:** These have characteristics of persistence: It assesses the stability in time of volatile and semi volatile compounds across substrates and conditions.
- **Transfer behaviour:** Interpretation of residues movement direct and indirect interaction on a forensic situation.

Qualitative summaries were combined with quantitative to suggest a framework of analytical model that can be applicable in forensic labs. The focus was on ways of reconciling science and practicality.

4. Chemical Composition Perfumes and Deodorants

The perfumes and the smells are very complicated chemical mixtures that will give the fragrance an identifiable and long-duration. The forensic usefulness of such chemical complexity is that, in a mixture of volatile and semi-volatile compounds, the traces of the products may be obtained and be compared and contrasted to the samples. They contain volatile organic compounds (VOCs) or essential oils or man-made aromatics, solvents, fixatives and stabilizers among other additives that make them long lasting and recognizable [31].

4.1 Volatile Organic Compounds (VOCs)

The most significant components in the fragrance are the VOCs and the largest contributor to the immediate smell of the scent following its application. They are alcohols, esters, aldehydes, ketones, and terpenes with strong polarities, and vapor pressure properties which can be readily separated and identified using the chromatography methods [32]. Other key fragrance personalities such as linalool, limonene, benzyl acetate and coumarin also have been seen to be reproducible in GC-MS profile and have widely been used in comparative analysis because of its retention time and mass spectrum properties [33]. Experimental studies also point at the fact that most of these compounds are short-term chemically inert when they are utilized in controlled conditions that qualify them as good specimens of reliable forensic indicators [34].

4.2 Synthetic Aromatics and Essential Oils.

The perfumes also contain many natural essential oils, that are botanical as the lavender, sandalwood, rose, jasmine and citrus plants. These oils consist of complicated mixes of percentages of terpenes and allied substances that will differ as per botanical source and the technique of extraction [35]. The synthetics formulations contain compounds that are aromatic compounds containing galaxies, ambroxan, tonalide and musk ketone. The fixatives and musks are relatively more long lasting and stable than the natural VOCs and are therefore applicable in investigating forensic forensics that necessitates old or aged residues [36]. [34].

4.3 Solvents and Propellants

The perfumes are often ethanol, water or a combination of both which dissolves the aromatic compounds to enable the volatile characteristics to be controlled. Deodorants that are aerosol propelled are usually manufactured using hydrocarbon propellants that include butane, isobutane and propane. The materials also can result in the leftovers of the materials in the surface which are identified in the analysis of the headspace or through the ion mobility spectrometry to differentiate between the liquid and aerosol deodorants perfumes [37], [38].

4.4 Fixatives and Stabilizers

The fixatives are also essential towards extending the smell concerning the inhibition of evaporation of volatile substances. The superficial VOCs have low molecular interrelations with phthalate esters, benzyl benzoate and other high-mass products and consequently reduced the evaporation rates [39]. Among the stabilizers that are used in inhibiting the oxidation and photodegradation of the fragrance blend to prolong its shelf life and time-of-stay on the surface are the BHT and octocrylene [40]. The volatile compounds are extremely helpful because they may be stored in the field in case the sample may be re-sampled in future or significant in a forensic case work [41].

4.5 Antimicrobial Agents and Additives

The deodorants are used on other chemical classes that are usually designed to render the body sweat and odor causing bacteria less active instead of the perfumes. The most common ones include aluminium chlorohydrate, zinc ricinoleate and triclosan among other antimicrobials. These components can be identified using the elemental or spectroscopic techniques using the ICP -OES and FTIR and also can give the chemical evidence during the forensic comparisons [42]. Preservatives, colourants, emulsifiers as well as polymer based stabilising agents are also included in deodorant to ensure that the formulation can be shown and that the majority of them will be ready on the skin or the clothing once the deodorants have been applied [43].

4.6 Forensic Implications

The interaction of the free action of VOCs, combined with essential oils, fixatives, stabilizers, and additives, is what creates the chemical profile, which is the one inherent to single products. Other parameters that create chemical peculiarities between brands and even product lines include production differences, ingredients supplies and batches formulations [44]. It can then move on to the analysis of the fragrance residue with a view of assisting the forensic investigators in determining some of the possible products that a trace material may have been deposited or by eliminating the sources. These components have different volatilities and persistence behaving properties and therefore it is an excellent blend of chemical pointers in the undertaking of forensic research [45].

5. Techniques of Analytic Detection

The analytical techniques determine the study of the evidence of the perfume and deodorant which can be able to identify volatile substances and semi volatile substances in small amounts. The fragrance formulation also are usually combined with spectroscopic and sensor-based to give the plausible qualitative and quantitative data [46].

5.1 Gas Chromatography-Mass Spectrometry (GC-MS).

GC -MS remains the most significant element of forensic aroma analysis since it is very sensitive and able to part and detect blends of volatile components of high complexity. The components of this method are resolved according to retention time and identified according to mass spectral libraries that offer typical fragmentation characteristics [47]. Sample preparation It is customary to use solvents either in solvent extraction or in headspace solvents with internal standards in most cases to enhance the precision of the quantification. It is proven that the GC-MS was able to distinguish between perfume and deodorant products based on the VOC ratios and the occurrence of specific fragrance markers of the product [48]. Thermal desorption GC -MS and pyrolysis-assisted GC -MS are the latest methods which enhance the recovery of the residues in porous or old surfaces of VOCs [49].

5.2 Solid Phase Microextraction Headspace Solid-Phase Microextraction (HS-SPME).

The method of HS-SPME is considered to be one of the most fulfilling techniques of extraction as it does not imply the usage of solvents and that the extraction of fragrance residues could be performed through the direct extraction of the VOCs in the air around a sample. Fibers are commonly coated with polydimethylsiloxane (PDMS) or divinyl benzene/carboxen (DVB/CAR) that adsorbs volatile substances that can be recovered at a later stage in a GC-MS apparatus [50]. The extraction conditions (temperature and exposure time) are optimized with the assistance of some conditions and this greatly adds to the sensitivity of the analysis and repeatability [51]. The specified method is especially required in the case of small sample size, as HS-SPME is non-destructive and may be applied to carry out a follow-up research with the help of other tools [52].

5.3 Advancement Liquid chromatography-tandem mass spectrometry (LC-MS/MS).

The use of GC1 -MS is excellent on the volatile compounds but LC1 -MS/MS is applied to detect non-volatile or semi-volatile compounds that are co-located with fixatives, phthalates, antioxidants and synthetic musks. The compounds will also be left on the substrates after the light VOCs have been lost, and they could be utilized in old or damaged samples [53]. LC-MS/MS is highly sensitive and the limit is particles-per-billion (ppb) using electrospray ionization (ESI) or atmospheric pressure chemical ionization (APCI) and very specific in terms of fragments [54]. This method is complementary to GC -MS as it is able to cover a larger part of the chemical composition of fragrance residues.

5.4 FTIR and Raman Spectroscopy

Non-destructive methods The FTIR and Raman are fast methods of establishing the occurrence of functional groups in the fragrance formulation. The trends of typical absorbance emitted by FTIR are associated with the carbonyl, hydroxyl, aromatic and other functional groups [55], and the vibrational modes identified by the Raman spectroscopic measures are barely conspicuous in the infrared spectra. A set of these techniques can be employed to categorize the samples according to the characteristics of the structure with slight treatment. The fact that at present portable FTIR and Raman devices are offered and may be implemented to perform a screening test prior to the access to the laboratory can also explain the growing popularity of these devices in forensic laboratories [56], [57].

5.5 Gas Sensors and Ion Mobility Spectrometry (IMS).

IMS is a fast and highly sensitive method that isolates ionized fragrances with different drift times that are in an electric field. It was initially used to detect explosives and narcotics, but has been discovered to have immense potential in detecting fragrances pattern since VOCs are capable of giving unambiguous mobility spectrums [58]. The other new alternative is the electronic nose (E-nose) systems which is a set of sensor arrays that are combined to replicate the senses of smell of the human beings. Along with machine-learning algorithms, e.g., support vectors machine or neural networks E-nose devices can identify perfumes and deodorants with a high level of accuracy, using VOC profiles [59].

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6. Persistence and Degradation Studies

The most significant things that should be taken into account when determining whether perfume and deodorant can be applied or not is persistence of the remains. Characteristic fragrance compounds can be recovered on the surface after deposition by the use of persistence. The physicochemical property of the compounds, substrate property and exposure to the environment are the basis of this behaviour. By being familiar with these, the forensic examiners will be in a position to be aware of whether the traces that have been found during a crime scene can be related to recent contacts or an old transfer phenomenon [62].

6.1 Physicochemical Determinants

Numbers of compounds comprise so many fragrance formulae with enormous volatilities. Linalool and limonene are terpene compounds that have low molecular weights and hence are readily volatile due to their high vapour pressure and heavy constituent chemicals like synthetic musks and phthalate-fixatives do not volatilise staying longer on surfaces [63]. Some of the studies indicate that fixatives in the light VOCs that retard the evaporation of the light VOCs and promote the detection of the light VOCs. These interactions are characterised in terms of the first-order kinetic models and they may assist in forecasting the behaviour of degradation in conditions of controlled laboratory conditions [64].

6.2 Influence of Substrate Type

The nature of the surface on which the residues of the fragrance are deposited is also a decisive factor in the time of detectability of the compounds. Cotton, wool and the majority of polyester blends are porous or fibrous hence more effective in trapping volatile and semi volatile components than hard smooth surfaces such as metal or glass. The compounds can be physically locked up in microscopic cavities of fibers in the textile to extend the persistence duration and slow down the volatilization [65]. In any comparative analysis, cotton and wool are always ranked as the first two after polyester and lastly the hard nonporous surfaces as persistence hierarchy [66].

6.3 Environmental Factors

Environmental situations lower the fragrance residue behaviour significantly when deposited. Specifically, temperature, humidity and exposure to ultraviolet have a special impact. Compounds with lower molecular weights can be evaporated and UV radiations will enhance oxidative and photolytic decadence to form new products that may not be readily analyzed using analytical techniques [67]. The humidity will have both adverse and beneficial impacts: mid level of moisture will enhance the adsorption onto the hydrophilic surface and the high level of moisture will increase the rate of hydrolysis and wash- off process. These differences claim that there is need to record the environmental circumstances in interpreting the fragrance evidence [68].

6.4 Time-Dependent Degradation and Kinetic Modelling.

The laboratory experimental data show that most of the fragrance compounds are unstable and in several predictable ways of kinetic occurrence. Volatile organic compounds (volatile) can have half-lives as short as many hours and heavy fixatives may have half-lives even days. A study done on linalool on cotton as an indicator has indicated that half-lives were about 8 hours and diethyl phthalate may last over 72 hours under the conditions [70]. Linear blends are not necessarily actually used to make fragrances as first-order models are common. Other materials like co-evaporation and competitive adsorption can give false patterns of decay to be experienced when they are in contact with each other as well as when multivariate analysis is applied to get the correct understanding[71].

6.5 Compound to Compound Interaction Effects

Perfumes are not single chemical compounds but complexes which consist of fractions. The fixatives tend to increase the stability of the less dense of the VOCs through weak inter-molecular associations and solvents are sometimes likely to accelerate the evaporation of part of the semi-volatiles. These effects of interaction might be composed of time-dependent residual composition, and are becoming crucial in forensic interpretation [72]. The residual analysis of the fragrances by thermogravimetric and chromatographic methods confirms that they degenerate in another succession and not in a sequential fashion hence multi-markeric analysis is imperative in the determination of the age of the residue [73].

6.7 Overview of Persistence between substrates

In total, persistence in bacterial cells and its use in bioremediation has been addressed in the current paper by discussing the most common or most widespread substrates and their degradation. Research has made general speculations concerning the predominant longevity of fragrances:

Substrate	**Dominant Retained Compounds**	**Detectability Duration (Approx.)**	**Main Degradation Factors**
Cotton / Wool	Polar VOCs, fixatives	48–120 h	Oxidation, light exposure
Polyester	Hydrophobic musk’s	24–72 h	Thermal loss, diffusion
Skin	Fixatives, semi-volatiles	12–48 h	Washing, sebum oxidation
Metal / Glass	Thin film VOCs	≤ 12 h	Evaporation, photolysis
Paper / Leather	Semi-volatiles	24–96 h	UV exposure, oxidation

Table 2 - Times of Persistence- Typical Under Controlled Laboratory Conditions.

The results of these tests compose the pre-test expectation of the stability of the residues and come in quite handy in the forensic reconstruction wherein time-since-deposition (TSD) is in effect to be employed.

7. Mechanisms of transfer and Casework Relevance

It is a very critical factor that the use of perfume and deodorants will impact a residue on a different surface, which determines their forensic utility. Depending on some conditions, it can be direct, indirect or limited airborne dispersion transfer. The fact that it has knowledge of the mechanisms that help such mechanisms allow investigators to think of the alternative usefulness of the mentioned residues as associative evidence and the background pollution [75].

7.1 Primary Transfer

Primary transfer occurs when the smell person approaches someone or an object that is close to him/her. This is the best way of delivery since fragrances will be used as the compound would be deposited at the point of contact. Residue transferred is dependent on the pressure, the time of contact and the nature of the surfaces that come into contact. The traces of VOCs on clothes or on the skin are proven to be left by the short-term contacts (a few seconds long) [76]. Frequent contacts or high pressure will only augment the amount of transferred residue. And indeed researches carried out, by GC-MS and HS-SPME have shown that the available fragrance load can be transferred up to 15-25 percent in direct contact between fabrics and skin, or fabrics-fabric contacts [77].

7.2 Secondary and Tertiary Transfer

Such transfer of the fragrance through an intermediate surface is referred to as secondary transfer. An example is the perfume on clothes which can be identified on the piece of furniture or bedding or even on another garment. In the secondary transfer, the perfume constituents are usually low in concentration (compared to primary transfer), but several of the semi-volatile constituents particularly the synthetic musks and the synthetic fixatives have continued to be detectable [78]. These residues can commonly occur either in dilute or modified form and it can therefore be difficult to determine how the transfer was directed. Nevertheless, the fixatives or less volatile substance is there that may be factoring in on the evidence on whether a residue is directly useful or through an intermediate.

7.3 Tertiary and Airborne Transfer

Less common is tertiary transfer which is caused by minimal concentrations of the VOCs that are transported across multiple surfaces or in the air within a restricted area. Micro-droplets, in this case, especially, can be supported by aerosolized deodorants that can become attached to the adjacent surfaces without necessarily coming in contact with them [79]. It is also likely that airborne transfer will also lead to the occurrence of very fine, diffusive particle deposits even though with the introduction of ion mobility spectrometry, and GC-MS techniques now they can be detected even in low-abundance residues in controlled settings.

7.4 Influencing Factors of Transfer Efficiency

The effectiveness of fragrance residues transfer between surfaces is influenced considerably by a number of physicochemical and environmental factors:

- Surface texture: The traces are more easily left on the surface of the porous and fibrous surfaces (cotton, wool) than on the smooth surfaces (glass, plastic) [80].
- Contact friction: or rubbing friction or repetitive motion leads to a great deal of residue migration [81].
- Compound volatility: The volatile components are easily and readily lost hence more volatile component is an advantage whilst less volatile components are not easily lost and hence remain longer.
- Conditions in the environment: the humidity, the state of air flow and temperature affect the opportunities of residue movement and its degree. Based on the knowledge of these variables it is possible to get to know that recovered residues are in connection with a meaningful contact or incidental contact.

7.5 Transfer Event Laboratory Simulations

Controlled studies of transfer situations have been done on a handful of occasions to give simulation of the conditions found on a forensic casework. In one of the experiments, the amount of VOCs deposited on the donor fabrics onto the polyester recipient fabrics after 1 minute contact was 10-12 VOCs which was able to be traced on the fabric, 48 hours later [82]. Other behaviour was noted with aerosol deodorants the initial transfer contents were smaller, because the volatilization process was rapid, but the fixatives and semi-volatiles were retained longer than desired, and the multiple compound groups analysis is significant [83].

7.6 Identification of Patterns of transfers Analytically

Both chromatography and spectroscopy data of the residue should be interpreted carefully so as to ascertain the dominant, or the minor source of transfer of the residue. Relative VOC ratios, retention times, and abundance pattern patterns of certain compounds are the most common measures that are undertaken by the analysts in deciding whether two samples have a shared common source. Part of the statistical justification is offered by the chemometric techniques (PCA (Principal Component Analysis), and HCA) that categorize the samples in terms of the level of similarity, and make the interpretation process more objective [84], [85].

Some of the investigative cases that require the investigation of fragrance remains include the assault cases, theft cases and sexual-offence cases. One such case is trace materials found on clothing, or personal items and they have been compared to substances that suspects were carrying around and thus helped in proving of links in time or contact situations when there was no DNA/fingerprints available to trace the suspects [86], [87]. But the evidence of fragrance should be deciphered with the greatest care. The thing is that there is a compound without being guilty. Rather, it must be used in conjunction with some other types of trace evidence like fibers, DNA, or information about reconstruction of the scene with the aim to come up with an integrated meaning [89].

8. Analytical Framework Proposal Perfume and Deodorant Trace Evidence

The technique that is methodological and repeatable must be developed to examine the remnants of perfumes and deodorant and make them more effective as a forensics evidence. Even though the quantity of different methods of analysis already exists, it is highly likely that the ways of how they are implemented to the labs may vary significantly. The suggested framework presents a combination of the procedures of the chemical detection, statistical, and chemometric processes to form a systematic process, which increases the degree of consistency, interpretation accuracy, and evidence level [90].

8.1 Reasons behind an Integrated Framework

Perfume residues are intrinsically convoluted mixtures of monumentally numerous volatile and semi-volatile compounds, which overlap chemically most of the product range. Normally, the comparison of chromatograms or spectral is not used through the traditional visual tools to be able to make a distinction between the related formulations. The subjective interpretation can be mitigated with assistance of the mixed methodology that presupposes a synthesis of analytical characterization and statistical modelling, with the help of which more justifiable conclusions can be drawn in the environment of forensics [91].

8.2 The Component 1: Wholesome Analytical Profiling

The former component of the scheme concerns the occurrence, in detail, with the chemical characterization through the help of the complex of chromatographic and spectroscopic apparatuses:

- Separating and identifying VOCs and light components-GC-MS.
- Trace volatiles extraction Solvent-free extraction HS-SPME.
- A single analyzer LC-MS/MS that was used to analyze heavy fixatives and semi-volatiles.
- Rapid FTIR and Raman Functional group identification.

The multi-instrumental technique has the benefit of providing a general representation of the quantity of fragrance compounds, and also enables the investigator to gain product-specific signals otherwise invisible when a single technique is utilized [92].

8.3 The Component 2: Data Pre-processing and Standardization.

Data standards of analysis Before interpretation Before interpretation Analytical data should be standardized in a way that there is similarity among samples. This includes:

- Repair of the chromatograms on the bottom.
- Maximum compensation to consider retention delays.
- Normalization of peak intensities should be made.
- Removal of artefacts or noise in instruments.

Pre-processing is needed to obtain stabilized chemometric data and it makes differences in variability due to instruments smaller or the state of preparation of samples.

8.4 The component 3: Chemometric and Statistical Interpretation

The objectivity of the analysis of the body of fragrance compounds in terms of the similarity of the fragrances and the probability of a match can be conducted by chemometric methods:

- Principal Component Analysis (PCA) identifies the trends of similarity by simplifying the data by plotting the most significant sources of variation [93].
- The Hierarchical Cluster Analysis (HCA) clusters the samples on the basis of the statistical distance and it assists in graphically displaying which residues have similar chemical properties.
- Machine-learning classifiers such as the Machine-learning (Support Vector Machine) and Artificial Neural Network (ANN) may be employed to categorize products with high classification rate with known reference sets [95].

These are the techniques used to help in corroborating the analytical data using the assistance of statistical evidence that makes the results in the area of forensic reporting more justifiable.

8.5 In this component 4: developing reference datasets

Reference Dataset Development Reference Dataset development is concerned with reference dataset development. Some of the major problems in the scheme include establishment of trusted reference collections. These libraries are supposed to contain GC-MS and LC-MS/MS profiles of most perfumes and deodorants and spectral fingerprints obtained in cooperation with the FTIR or Raman. These types of datasets can be compared directly with unknown residues and minimize the ambiguity of the attribution of the source [94].

8.6 In this component 5: validation and cross-laboratory consistency

The scheme promotes the validation of the analytical procedures according to the standards of various entities like ENFSI, ISO/IEC 17025 and ASTM. The extraction efficiency, detection limits and precision and repeatability verification have the advantage that they require that the methodology is scientifically sound and can be reproduced in laboratories [96]. The scientific validity of the analysis may also be strengthened by using inter-laboratory calibration exercises that will introduce consistency to the fragrance residue analysis.

8.7 Component 6: Forensic Interpretation and Reporting

It is also the last step of the framework that talks about the interpretive practices. It is anticipated that, the environmental factors, along with the chemical results and the statistical results will direct the conclusion by the analysts. Reporting based should be made using clear, transparent and defensible guidelines and it should include: The level of similarity between evidence samples and reference. This improves the quality of fragrance residues as evidence relating them across in a reasonable way in court [105].

9. Identified Research gaps and Future directions

Despite the fact that, in the long term, it is quite possible to achieve rather high progress in the area of forensic analysis of fragrances, there are still several methodological and interpretative problems, the presence of which complicates the additional extensive implementation of the method in the investigation of crimes. These are the weaknesses that it should control as a mechanism of rendering it possible to research perfume and deodorant remnants as trace evidences.

9.1 It lacks standardised analytical procedures

The other vacuum that is always happening is that internationally agreed procedures of collection, preservation, extraction and interpretation of fragrances residues are not present. The current activities at each of the laboratories are heterogeneous and hence, irregular, partial data quality and reporting standards. These inconsistencies make the process of comparing the outcomes of the research complicated, at best, and the extra polability of the use of the fragrance residue evidence in a crime [22]. Numerous things would be accomplished in this field developing standard guidelines like in the case of DNA, fibers or ignitable liquids.

9.2 In this case, the validity of the environmental measures is limited.

Many of the published papers of fragrance persistence and degradation are conducted in a controlled lab environment. The manner in which the residues behave within the environmental conditions i.e. variability in temperatures, air movement, humidity and sunlight drainage however can drastically vary in the real world scenario [23]. It does not have systematic research involving outdoors or field studies that can give a minor portion of information about the kind of fragrance remains on different surfaces in normal life. It is also necessary to possess larger scale environment tests that would more accurately measure time-since-deposition (TSD).

9.3 Within the chapter, there is a lack of centralized reference databases

The threat of the non-existence of centralized reference databases is there. The second important disadvantage is that there is not a single or reference database of commercial products of perfumes and deodorants that is chromatographically or spectroscopically. The data of perfume is shared through different groups of research and brands as compared to the DNA or finger print databases. It makes the process of source identification more difficult in comparison, and reduces the chances of carrying out automated source attribution [24]. An attempt towards creating standard reference libraries would be a good step toward improving reproducibility and application of machine-learning to fragrance profiling.

9.4 Statistical interpretation is questionable in nature.

This is the uncertainty in the interpretation of statistics that is the incapability to establish whether a statistical figure falls within a computerized range of certainty such as the p-value of a t-test that is less than 0.05 (Calhoun, 1994). Although chemometric tools such as PCA, HCA and SVM have used to make the interpretation of the data more objective, most of the studies that have been carried out so far do not give any definite outline of statistic threshold beyond which two samples may be considered a match. The legal context can be cited in support of the argument against the effects of the evidence of fragrance comparisons, wherein there have not been some standardized modes of probabilistic procedures or likelihood ratios [25]. Research directions in the future ought to be directed to the definition of validated statistical paradigms of stating similarity with the help of similar terms that are measurable and can be established in a court of law.

9.5 Under representation of Complex Substrates and Real Case scenarios.

The experimental studies are conducted on experimental materials like cotton or glass which is of clean grade and laboratory grade which form the majority of the experimental materials. Nevertheless, in most cases, it is a combination of casework, dirty surfaces or old-fashioned materials are typically the rule. It is important that the practical implementation of the behavior of fragrance residues on these complicated substrates is the key to the process of enhancing interpretation in the practical context of forensics. In the same vein, there are few research works which provide real-life example of the evidence of fragrances. It will be further explained using notes of real life studies which will help in establishing the practical limitations and reinstating the empirical evidence of fragrance residues as an evidence in the court of law.

9.6 Future Directions

The future research needs to be directed towards the inclusion of alternative analytical systems so as to include the chromatographic and spectroscopics and sensor based systems to introduce more variety of fragrance compounds [106]. It is possible that the future development of the artificial intelligence will assist the process of the pattern recognition further advancement, however, they should be reliable samples. It will also involve researching the model of degradation and transfer by longitudinal studies to establish the impact of the surrounding, man activity, interaction of the substrate. The cooperation between the fragrance industry and the academic institutions and forensic laboratories would guide towards the timely creation of the database and development of the standard operating procedures. The mentioned gaps can be brought in order to make sure that tool with a high evidentiary potential.

10.Conclusion

Analysis of the residues of perfumes and deodorants provides a potential, but still underdeveloped field of forensic chemistry. As it has been revealed in this review, fragrance formulations have unique chemical signatures due to their varied combinations of volatile and semi-volatile compounds, fixatives, stabilizers, and additives. These chemical markers can be detected in the trace level when assisted by sensitive analytical methods, including GC-MS, HS-SPME, LC-MS/MS, FTIR, and Raman spectroscopy and be used to differentiate the type of product or link the residues to possible sources [107]. Persistence and transfer studies indicate that fragrance deposits may persist on a broad range of substrates in hours or even days depending on the volatility, properties of the surface and environmental contact. Such observations are specifically applicable in the reconstructions of times, assessment of contacts, and secondary interpretations in instances where the biological traces are feeble or missing. Transfer studies are also emphasizing that the fragrance residues may be transported via primary, secondary and even airborne routes, which underline the necessity to pay close attention to the contextual consideration when interpreting any given forensic evidence [108]. Chemometric and machine-learning methods further enforce this by providing objective comparisons of complicated chromatographic data. PCA, HCA, SVMs, and ANNs are techniques that allow differentiating between similar formulations and minimize subjective bias and provide a more structured and statistically defensible ground of interpretation [109]. Nevertheless, there are other challenges that the discipline still encounters such as standardisation of analytical protocols, environmental validation and unavailability of centralized reference databases. It is of essence to incorporate these gaps to enhance reproducibility and win favor in forensic case work. In general, the creation of a unified analytical model, as suggested in this review, offers a way of making the fragrance residue analysis more uniform and more scientifically sound. Forensic practitioners can also improve the evidentiary value of traces of perfume and deodorants and advocate their acceptability in the case through the combination of proven analytical techniques, reliable-data-processing schemes, and clear reporting patterns. Further investigation and inter-disciplinary cooperation will be necessary in order to provide fragrance residues with a full-fledged and well-known status as a subdivision of trace evidence [110].

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Author Contributions

Architha M. R. helped in the conceptualization, data collection, literature review and writing the manuscript. The research was guided by a researcher Dr. Srinivasa Rao Gundu, who supervised the research, did experiments validation, revised the methodology of analysis, and polished the final manuscript to be published. This work was finally read and endorsed by both authors.

Conflict of Interest Statement

The authors of the article report no conflict of interest with regard to the writing or publishing of this article. The entire information and conclusions found in this review are premised on published scientific sources only.

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