Forensic Science International: Synergy 6 (2023) 100307

Contents lists available at ScienceDirect

Forensic Science International: Synergy

journal homepage: www.sciencedirect.com/journal/forensic-science-international-synergy

Interpol review of fibres and textiles 2019-2022

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A R T I C L E I N F O

Keywords:
Textile fibres
Transfer
Trace evidence
Forensic science
Significance of evidence
Evidence interpretation

1. Introduction

This review deals with relevant literature in the field of forensic examination of fibres and textiles. Several topics are represented in order to cover the numerous steps and aspects of this kind of examination, but also to interest various types of readers, from practitioners with different task levels to forensic managers, as well as legal end-users of expert's reports. It is a continuation to our previous review [1] and covers publications between January 1st' 2019 and December 31st' 2021. Publications from the year 2022 are not included in the present review.

2. General

A very comprehensive review [2] of scientific foundations and current state of the art concerned five types of trace evidence: hair, fibre, tape, paint and glass. The review is introduced by a global overview of education and training, proficiency testing, and trace evidence interpretation and report writing in forensic science on a worldwide scale. Regarding the fibre section this review reports a lot of relevant publications for various aspects of fibre and textile examinations. A new practitioner in the field will appreciate to easily find this overview of citations presented in a didactic and exhaustive way. However, the reader should not expect a ready-made summary of relevant data but rather an invitation to explore more deeply the cited literature.

Five handbooks were published over the last three years and their availability is to be mentioned for the interested readers. The first one concerns analytical techniques for forensic samples [3], combining both conventional and emerging techniques. The second one [4] is focused on thermal analysis of textiles fibres and it contains detailed chapters dedicated to natural fibres and to different types of common synthetic fibres. The two other ones are fully dedicated to natural fibres. The 2nd edition of the Handbook of Natural Fibres is divided in two volumes that can provide information on identification and testing of several types of natural fibres [5] and on some applications [6]. The 1st edition of Fundamentals of Natural Fibres and Textiles [7] describes natural fibres – and regenerated fibres as well – in terms of processing, properties and applications. Finally, a handbook covering all aspects of microscopy in forensic fibre examinations was published by De Wael [8]. This handbook is discussed further in this review (Section Instrumental Techniques, Microscopy).

Buzzini and co-authors [9] published a philosophical discussion on the nature of the "trace" wording. Nowadays the term "trace" is often used as an adjective to connote the small size of materials (i.e. fibres and other microscopical debris) used to make various associations between individuals, objects and places. Considering the Locard's exchange principle traces at the crime scene are not restricted to a small size. Traces are basically remnants of physical activities and their relevance must be assessed when used in the investigation of a particular event. Trace evidence should be viewed more broadly in the context of "interrogatable traces" (physical traces can be intelligently interrogated to develop an understanding of many of the physical details of an event like a crime) which contributes a value-added source of information for the reconstruction of a case and may be used to address activity

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https://doi.org/10.1016/j.fsisyn.2022.100307

questions rather than merely an endeavour seeking source attribution ("associative trace").

The forensic literature shows a clear trend towards increasing use of chemometrics (i.e. multivariate analysis and other statistical methods) as already mentioned in the Section 12 (The future) of the previous Interpol review [1]. Bovens et al. [10] are part of the STEFA-G02 European project which is intended to create a guideline on how to apply chemometrics in forensic drug investigations (but not limited to) as well as developing an open source software tool [11] to facilitate the application of these methods in a structured way. Forty-one articles recently published (2011–2018) in forensic and chemometric journals were collected. Data were categorised in two types for standardisation purposes: low-dimensional datasets (25 articles, mostly about GC-MS techniques) and spectral datasets (15 articles, mostly about MIR techniques). The most common operations used relate to data pre-processing (normalisation and transformation) and data processing/reduction (Principal Component Analysis, Discriminant Analysis and Cluster Analysis). The purpose of using chemometrics was in two-thirds of the articles a question of classification and a question of comparison in the remaining articles. In cases where grouping or comparison is needed, chemometrics provide a single value (degree of similarity) that may facilitate further data interpretation and formulation of the forensic report. Other information available in the forensic case (e.g. colour) can serve as a pre- or post-selector but will not be used in the chemometric analysis itself. Additional research dedicated to fibre analysis is to be found in the MSP section of this review.

3. Case reports

Coyle reports on a fibre case conducted at Contact Traces and where he was asked to reinvestigate the murder on David Watkins [12]. The first part of this series of publications describes the context information and the review of the paperwork. The victim was found shot and killed in January 1993. An arrest was made 10 days later and Andrew Everson was brought to court in February 1994 but acquitted for the murder on David Watkins. The forensic case solely relied on the fibre evidence where 39 fibres (3 different fibre types) were found on the victim's clothing matching the constructing fabric of the car seats of Andrew Everson's vehicle, a Peugeot 309 GTi. The fabric of the car of a victim's friend, Mr. F. was found to be indistinguishable from the fabric of the suspect's car and the victim was known to have been in that car a month prior to his death. Industrial enquiries were carried out in relation to the occurrence of this fabric. The expert stated that the presence of the fibres are highly significant and in relation to the contact with Mr F.'s car that it is extremely unlikely that so many fibres would remain on the victim's clothing for this period of time. Information from the case was reviewed in depth and all laboratory notes were inspected in detail. Concerns with respect to contradictory TLC results, observed differences in one of the fibre types from the car fabric samples and the impact on the relevance of the industrial enquiry are raised. The second paper describes the new investigations carried out in the laboratory by Coyle [13]. After relabelling every mounted fibre with a unique number, the case is treated as if it were a new case. The control samples from the car are re-examined solving the ambiguity of the differing grey thread fibres and excluding the friend's car as potential source of the trace fibres and adding a constituent known fibre type from the sides of the seat which were not taken into account before. Subsequently it was decided to examine tape liftings taken from the car seats of the suspect's Peugeot 309 GTi with the aim to identify relevant fibre populations that could also be searched on the victim's clothing. Striking amounts of long red polyester fibres were found on these car seats and 4 matching fibres on the victim's clothing, as well as four other fibre populations that could be identified after a database-approach of the trace fibres present on the car seats. These findings further strengthen the initial results of the case. In the final paper Coyle explains his interpretation of the fibre evidence and the process of submission of the results to the Court of Appeal [14]. The relevance of the five matching fibre types from the constructing fabric of the suspect's car on the victim's clothing and the five fibre populations found on the car seat of the suspect's car and the victim's clothing is discussed in terms of persistence and transfer, as well as the assessment of the results with regard to Mr. F's car. Coyle expresses that in his opinion, the findings provide extremely strong scientific support for the proposition that the clothing worn by David Watkins was in recent, direct contact with the interior of the vehicle owned by Andrew Everson. An attempt for a 'thought experiment' where a time frame of contact between the victim and the car seat is proposed based on the number of fibres found on the victim. This reasoning was however disputed by the defence expert witness. Finally, Andrew Everson was re-tried for the murder of David Watkins and was found guilty and sentenced for life imprisonment. This is an example of a very unique double jeopardy case where the physical evidence is dominated by the fibre findings.

De Simone et al. [15] give us an insight in a murder case disguised as a car accident. A male victim is found at the edge of a street. The deceased's son states that he had an accident with his father sitting in the front seat. He dragged his father out of the car and left the scene when he realized that his father had died. Autopsy findings and CT scan were compatible but small fragments of fabric were found by the pathologist on the damaged front lights of the car matching the fabric of the deceased's jacket. These findings support the proposition that the victim was hit by the car as a pedestrian.

4. Damage analysis

4.1. Textile damage

In the period prior to this review several authors had commented on increasing the standardisation and interpretational framework for forensic textile damage analysis [1]. The PCAST report released in 2016 also highlights a need for clarity about the scientific standards and for the validity and reliability of forensic methods for feature-based methods in general.

Australia and New Zealand have created a Textile Damage Working Group to assess these points and assure improvements in the evidence type in terms of consistency and training. A review on the current state of textile damage examination in Australia is now published by Sloan et al. [16] to further address the issues raised in the context of the PCAST report. The review covers the current state of a standardised examination framework, the impact of cognitive bias, requirements for training of the forensic practitioners, and gives an overview of a few interesting Australian case examples. It is noticed that there is a need to provide and support opportunities for training and continuous professional development on textile damage examination. There is a need of knowledge of the fabrics, yarns and fibres to know how these textile properties can impact the damage and some case studies highlight that different aspects such as prior knowledge of the case circumstances as well as the lack of knowledge of specific case circumstances can have an influence on the interpretation of the examiner. Finally, some practical measures are proposed to counter the effect of cognitive bias.

The morphology of textile damage caused by sharp objects such as knives was explored by several authors in the period covered by this review. The interested reader will find the general features of stabbing damages in the established literature. Carr et al. review some of this literature in a publication where they aim to increase the awareness around the use of edged weapons for forensic scientists [17]. Their publication covers a review of the available information regarding the use of such weapons (frequency of incidents, stabbing mechanisms, anatomical target) and regarding textile damages and stab wound injuries but also adds insights in different grips of a knife. It is interesting for a forensic practitioner to see the different techniques that a trained attacker can use to hold a knife and that will influence the stabbing mechanism.

Some of the other recent contributions focus on specific properties of textile materials or the stabbing event and the influence on the damage morphology.

Aliverdipour et al. studied the effect of the fabric's tensile behaviour on the penetration resistance in a stabbing event [18]. They tested five objects (three knives and two spikes) on different types of textile materials (shirting fabric, worsted, elastic denim, artificial leather and tarpaulin) and compared the penetrating force, depth and energy between the different objects and textiles. They found that the geometrical characteristics of a knife as well as the tensile strength of the textile have an impact on the penetrating parameters and the shape/extent of the damage. An increase of the tip angle of a sharp object (more blunt object) will give a higher penetrating force, depth and energy. The same is observed for fabrics with a higher tensile strength, the tarpaulin fabric having the highest tensile strength and also displaying the highest penetration force followed by denim, leather, worsted and shirting fabric. Although the following conclusion is not highlighted by the authors, it appears from the analytical data that the tip angle has a much higher impact on the penetration force and energy than the textile's tensile strength. Nichols-Drew et al. also looked at rounded tip knives in a preliminary study where they compared damages with five different kitchen knives in four different textiles; t-shirt (knitted cotton), denim jeans (twill woven cotton), long sleeved top (knitted synthetic blend) and skirt (non-woven faux leather) [19]. Although some limitations of the preliminary study are highlighted by the authors it can be concluded from the experiments that the resulting damage is visibly different, depending upon the corresponding knife and that a knife with a good rounded tip has the least chance to penetrate a fabric. In this study a knife with rounded tip did not penetrate at all any of the selected garments in their experimental stabbing setup. The knives with pointed tip also produce longer damages. In agreement with the other findings [18] the authors also conclude that the resulting damage is affected by both the blade tip shape of the knives as well as the fabric that is involved.

An in depth-study of the influence of the structure of a fabric on the stabbing resistance was performed by Li et al. for the particular case of personal body protection garments fabricated by HMWPE yarns [20]. They find that the structure of a fabric has a crucial role in the resistance against stabbing/penetration. Research into the double or multi angle pass stabbing has shown that increasing the thickness of the HMWPE-based fabric has an impact on the stab resistance, as well as the structure, where the orthogonal/through-the-thickness (O/T) structure offers the best resistance. The direction of stabbing will also affect the resistance, with the 90° direction (perpendicular to the weft yarns) having the highest resistance. The penetration resistance of personal body protection garments can also be enhanced by utilizing metal threads in the fabric structure. Amirshirzad et al. have studied the effect of metal threads on the penetration resistance by using different diameters, number of threads, the weave pattern, multi-layer systems and the stabbing angle [21]. When adding metal threads to a fabric the penetration of a sharp object will be more difficult. The higher is the number of metal threads in a fabric, the higher penetration will require force and energy. The influence of the number of metal threads was significantly higher than an increase of the diameter of the thread. Prominent factors like weave pattern and the fabric density must also be taken into account. Weave patterns with more firmness can limit yarn movement increasing the protection ability. Double-layer metal reinforced fabrics resulting in a grid of metal threads provide further restriction of the knife movement and increase the penetration resistance.

Simulation trials can sometimes be very useful in knife crime cases. Currently these simulations are often conducted by manually performing the stabbing action. Sloan et al. [22] asked 40 participants to approach a target from the front and from behind while performing a stabbing action with three different knives (utility knife, hunting knife and machete) and investigated the impact of the knife type on the actions taken by the operator. They observed a variation in arm movement where participants mostly used the smaller utility and hunting knife in underarm thrusting or overarm hacking actions and an overarm hacking action or combined hacking/slashing action when using a machete. The stab position and velocity were also investigated. From the study it can be seen that the individual himself introduces a variation. Standardisation of simulation experiments through the use of mechanical or robotic systems would be an advantage to eliminate the natural variation that is now seen in human stabbing simulation.

Fenton et al. contribute to the subject of simulation trials for stabbing events with a review on skin and skin simulants [23]. Although pig skin is the most common used for reconstruction purposes, synthetic skin (a polymeric material) would be more functional, because the variability is much less and the physical and mechanical properties can be manipulated to those of the real skin and can be adjusted for different body parts. Pig skin also appears to be much thicker than human skin.

De Luca et al. show that mushroom-shaped morphology in synthetic fibres [24] and other physical characteristics like rupturing of the yarns and fibrillation/splitting of the fibres are useful patterns for assessing the presence of a bullet impact. They examined the textile remains of six individuals executed in the period 1973–1990. Further quantitative studies will be needed, because there is a high variability between the textile and the bullet types.

Finally a review of forensic physical fits [25] covered physical fits in casework in different types of expertise including textile materials. It was concluded that despite limitations, physical fits are still considered the highest level of association between two items. A difficulty in the examination of clothing could be the medical cuts induced in a victim's clothing later on.

4.2. Fibre damage

Textile materials change after exposure to heat [26]. The authors examined blends of cotton/polyester textile materials that were briefly exposed to an incident heat flux of 10 kW/m^2, causing a damage on the microscopic scale, not visible to the naked eye. They found scanning electron microscopy a very suitable technique for tracking morphological changes in fibres due to heat exposure and could identify changes in the chemical structure of exposed cotton fibres by the use of FTIR. The authors also draw attention to a singeing step in the production process of textile materials which also involves an exposure to heat source and has to be considered in the interpretation of this type of examinations. Furthermore, the extent of the damage depends on the porosity of the fabric, there is less resistance when there is a greater porosity. Looking at the difference between polyester and cotton fibres in blended fabrics, the change of morphological structure occurs faster for the polyester fibres whereas a change in chemical structure is more readily seen for the cotton fibres.

Another study [27] concerned the degradation by light in natural fibres. They looked at the photodegradation of individual fibres from wool and cotton fabrics (dyed with CI Acid Red 27 and Direct Red 80 respectively) by placing them in a Light Fastness Q-Sun 1000 Xenon test chamber. They observed the photodegradation process which occurred in all samples with no major differences for cotton or wool. The fading of these fibres being variable the extent of photodegradation remains unpredictable in nature where the sunlight cannot be controlled. However, the findings suggest that forensic examiners should be aware of the photodegradation effect when case examinations are carried out on fibres which have been exposed to sunlight.

A DU-PLS algorithm was used by Mujumdar et al. [28] to investigate the effect of extreme weathering conditions under different time intervals up to 12 months (desert in Arizona and humid environmental settings in Florida) on the fluorescence of dyed textile fibres (cotton, nylon and acrylic). They were able to discriminate fibres between the non-exposed fibres and the exposed fibres to both dry and humid conditions. A significant loss of fluorescence intensity was observed. The period of exposure for the two weathering conditions could also be discriminated, as well as the fibres exposed to dry and humid climates for the same period of time. Acrylic fibres are harder to discriminate since these fibres have a good thermal stability in comparison to the cotton and nylon fibres which are more sensitive to weathering and photodegradation.

Dolan et al. [29]) examined the persistence of the coatings of fluorinated oil-and-water-repellent fabric coatings and spray-coated fibres after outdoor weathering and laundering, with an encouraging result. By the use of gas chromatography and pyrolyzed samples the coatings were still detected after 12 weeks of outdoor exposure and on 95.5% of the samples laundered up to 10 wash cycles. Spray-coated fibres are seen as less durable.

The influence of decomposition fluids on clothing [30] was investigated by burying seven pig carcasses with each wearing a cotton t-shirt, polyester briefs and polyester-cotton socks, along with seven control graves containing this identical clothing. The carcasses and control graves were exhumed after 1, 3, 6, 9, 12, 18 and 24 months. After 12 months the cotton t-shirt from the control grave were fully disintegrated. Pig remains and therefore also the decomposition fluids had a protective influence on the t-shirt which was more preserved than the control samples. Only discolouring and staining was seen at the polyester fabric for both control and pig graves whereas the blended socks had a similar process than the cotton fabric. The authors suggest that the decomposition fluids improved the preservation of the textiles (especially for the cotton materials) and with the use of infrared spectra and decomposition by-products it could be possible to get information from the timing of events and the indication if a body was decomposing at a specific site.

5. Significance of evidence

5.1. Data from forensic research

To assess the significance of the fibre evidence, a fibre expert will rely on different sources of data. To assess fibre type frequencies, fibre databases and population studies provide valuable tools and/or sources of information whereas for transfer and persistence probabilities, the fibre expert will search for comparable transfer & persistence studies in literature or will need to perform case-specific simulations him- or herself. Unsurprisingly, many research as well as discussions in fibre evidence are focussed on these topics.

In theory fibre databases are extremely suitable to assess the frequency of a fibre type. If search functions are available a frequency of appearance can easily be calculated within the fibre database. However an ideal fibre database is hard to find and frequency calculations are often prone by limitations and discussions. De Zwart and van der Weerd [31] proposed a methodology to filter the contents of a database such that only items that are considered relevant are selected. This is further discussed under in the section Evidence Interpretation.

In the previous Interpol review [1], it was mentioned that a fibre database was developed by Powell et al. to support them in their work dealing with a huge cold case investigation. In their next publication the authors discuss how their database was used in this major cold-case investigation [32]. Powel et al. developed a database-driven comparison strategy that allowed them to handle and compare large numbers of fibre traces (>10 000 fibres). The database allows for an MSP comparison of all traces with all traces resulting in a pregrouping of similar fibres, facilitating the process in intelligence-based cases. In their paper, the authors also highlight the care that must be taken in reporting potential associations for intelligence-based cases, where the source of textile of the fibres is unknown.

Muehletahler et al. show the potential of internet web crawling and web scraping tools in gathering data related to fibre frequencies, as alternative for traditional databases or population studies [33]. In less than 24h they extracted 68 text-based fields describing a total of 24 701 clothes from online clothes retailers. According to their searches cotton, polyester, viscose and elastane are the 4 most recurrent fibres types, with cotton being the most abundant (80%). The most common colours are white, black and blue. The authors recognize that the most complicated and laborious classification field was the codification of the colour. Colour brand names make it more difficult.

In Canada, a knowledge database was constructed by Cadola et al. [34]. This database structures literature covering transfer, persistence and population studies in different fields such as DNA, hairs, fibres, etc. Therefore, the aim of the database is to offer a tool for experts facilitating the interpretation at the activity level. 2042 peer-reviewed publications currently are introduced in the databases and search options provide for the possibility to classify the publications by different criteria such as the type of trace, year of publication but also type of study and/or type of trace. The database can be accessed by all via the Laboratoire de Recherche en Criminalistique webpage [35]. In their publication the authors also show some tendancies in literature. DNA, biological fluids and gunshot residues have the highest number of publications, followed by fibres. Most publications focus on transfer studies and 46.4% of the publications come from European countries.

The transfer of fibres in a stabbing event was investigated by Sneath et al. [36] They tested 3 different types of weapons (knife, scissors, screwdrivers) and 3 different garments (cotton, polyester and linen-viscose blend) in a setup where the garments were placed over a polystyrene block and the weapon was used to stab from a 50 cm distance. 10 repeats were performed for each test. Prior to the experiment the sheddability of the garments was tested and the cotton garment was found to shed fibres the easiest. The transfer of fibres was found to be highest for the linen-viscose garments and lowest for the cotton garment (in case of the knife). Examining the textile damages and observing fraying of the edges of the damages in case of the linen-viscose garments compared to a clean cut in the cotton garments led the researchers conclude that not the sheddability but the textile construction causing pronounced fraying or not, is the determining factor in the transfer of fibres. In case of the knife, mean values of 73 fibres, 167 fibres and 228 fibres transferred for respectively the cotton, the polyester and the linen-viscose garments were found. Skokan et al. performed a study with two kitchen knives (straight and serrated blades) and four blended textiles and found that the transfer mainly lies on the properties of the fibres. Since cotton fibres are shorter, less resistant and less elastic than polyester fibres, they are favoured during transfer and can be found in greater proportion [37]. A study of background population of fibres on knife blades was conducted by Cammarota et al. [38] The number of groups found per knife varied between 1 and 3, each group containing between 2 and 6 fibres. 16 knives sequestered by the police were subjected to fibre recovery protocols including tape lifting.

Skokan et al. also studied the fibre transfer mechanisms of blended cotton and polyester textiles [39]. The objective of this study was to test the transfer capacities of blended textiles of different cotton and polyester proportions by performing several simulations under controlled conditions. The results were correlated to the fibre type, morphology, and size. A shedding ability and a primary transfer capacity were separately tested. The result suggest that cotton fibres are favourably transferred when compared to polyester fibres. None of the individual parameters seem to stand out in explaining the differential shedding of fibres. As a consequence the most plausible explanation would be a combination of the length of fibres (initial length in fabric construction), fibre arrangement (yarn construction) and the type of fabric (knit or woven). Additionally, the authors conclude that the shedding test using an adhesive tape and constant pressure may overestimate the transferred proportion of cotton fibres to be expected following a real contact.

An interesting approach was followed by Sheridan et al. when they investigated fibre transfer in a contactless scenario [40]. Volunteers were situated in an elevator (semi-enclosed environment) and primary and secondary contactless transfer scenarios were investigated. It was found that fibres can be transferred to the recipient garment by air movement solely, but in smaller quantities as would be expected for a physical contact scenario. The sheddability of the donor garment had a great influence on the number of fibres transferred. In the case of cotton or polyester donor garments, up to 66 and 38 fibres were found to be transferred as opposed to 1 or 2 for the acrylic and wool garments. The characteristics of the fibres themselves (influencing their potential to stay in the air) is also expected to have an influence on the transfer probability. These results should be considered in cases where fibre evidence rely on small amounts of trace fibres.

The persistence of fibres on static textiles was studied by Prod'hom et al. [41]. They conducted a series of experiments considering four factors under controlled conditions; time, inclination of the recipient textile, wind speed, and rainfall and in parallel collected data from experiments in actual outdoor conditions and next to a weather station. From the laboratory experiments the authors conclude that wind speed and rainfall have a major impact on the persistence of the fibres, whereas time and inclination of the recipient textile were found to be nonsignificant. The results from the outdoor conditions were less predictable. The persistence of fibres is found to be linear in time unless extreme weather conditions are involved. Then exponential fibre losses are observed. The aim of the study was also to calculate fibre losses based on model predictions from the laboratory data. The authors report on some challenges that were faced regarding this objective.

Prinsen et al. studied the modus operandi of smothering by asking 181 music festival visitors to try to smother a dummy [42]. The actions were recorded on video and different parameters such as alcohol and drug use, the length of the participants and main placements in relation to the smothering time and/or the smothering force were monitored. It was noticed that only few participants spontaneously sat on the right side of the bed with the dummy. It is believed that these results could help forensic examiners in determining relevant contact zones in case of smothering but no actual microtrace comparisons were carried out.

Caccia et al. [43] examined the persistence of microtraces from different types of traces (from painted wooden bar, cotton vest, woollen vest, soil, brick and mortar wall and ivy) under the nails of individuals carrying out their daily activity up to 24h after transfer. Cotton fibres could be retrieved even after 24h under the nails, whereas wool target fibres were found up to 8h after transfer. Because the two types of fabric behave differently it is impossible to identify a relationship between the type of scratched material and its persistence, therefore further studies would be interesting.

Finally, Was-Gubala et al. performed a study on the characterisation and discrimination of so-called metallised fibres found in clothing and decorative materials [44]. They analysed 36 samples purchased on the Polish consumer market using optical examinations, FTIR measurements and SEM-EDX analysis and were able to subcategorise the different samples based on the results from optical microscopy (colour, morphology and diameter) and elemental composition. Not all samples of glossy textile products did indeed contain so-called metallised fibres. The information given provides valuable information for the forensic practitioner regarding the discrimination and evidential significance of these fibre types.

5.2. Data from microplastic research

Another area of expertise seems to gain in interest. The world of microplastics is also related to fibre evidence and although these publications are written more in a concern of the environmental and health impact, some data from these work could also be used in assessing the significance of the fibre evidence. In the following, only the results regarding fibres will be discussed (not microplastics).

Prata et al. reported on the presence of microplastics and fibres found in the Douro river in Portugal. [45] They sampled three areas in the river; one area in the countryside, one in a wastewater treatment effluent release zone and one in proximity to a boat dock and maintenance station. The median concentration of fibres found in the Douro river was 46 F/L. The average and median size of these fibres was 522 and 315 μm, respectively. Most of the fibres were natural (62.6%). 14.4% of the fibres were suspected to be synthetic. The abundance of the synthetic fibres increased downstream with 5.6% in the countryside, 13.1% at the wastewater treatment effluent zone and 22.3% at the boat station. A similar study was performed in the indoor air of living rooms of five houses in Aveiro, Portugal. A median of 0.9 fibres/m^3 was found [46]. Based on visual analysis 19.6% of these fibres were classified as synthetic fibres and 58.7% as natural. The dominant colours were yellow for the synthetic fibres and white for the natural fibres. The length of the fibres was in median 881 μm for the synthetic fibres and 519 μm for the natural fibres and with a maximum length of 10822 μm. A third study aimed to assess whether microplastics contaminate the air in central London [47]. The deposition rate of fibrous microplastics was calculated to range from 510 to 925 fibrous microplastics/m^2/d with an average of 712 ± 162. The most abundant lengths were 400–500 μm. Fibre frequency increased with decreasing length suggesting the presence of more shorter fibres. 17% of the fibres were synthetic with PAN being the most abundant fibre type (67%) and PET the second (19%). These samples were collected over winter and from a nine-story high roof at a riverside urban site in Central London and taken twice a week for 4 weeks. Stanton et al. confirm in their study of freshwater and airborne textile fibre populations that natural textile fibres constitute a significantly greater proportion of environmental textile fibre populations. [48] However, they also point out the importance of visual characterization in the case of fibrous microplastic pollution, as to opposite of relying only on FTIR. Textile fibre concentrations were also found to vary greatly through both space and time. Finally, O'Brien et al. looked at the airborne emissions of microplastic fibres from domestic laundry dryers [49]. They observed an increase of fibre concentration in samples from the ambient air during operation of the dryer compared to the blanc samples confirming mechanical drying as an emissive source of fibres into indoor air. For their studies they used a polyester fleece blanket.

6. Evidence collection/recovery

In the framework of a validation study to validate crime scene fibre retrieval processes, the effect of tape type (Crystal Tabs or J-LAR), tape storage (−5 °C, room temperature and 35 °C), taping method (zonal or one-to-one) and different surfaces (commonly encountered at crime scenes) on the fibre recovery was investigated and viewed with the ANOVA model [50]. The results of the study show that fibre recovery is more efficient when using the Crystal Tabs tape compared to J-LAR tapes, with tape storage at a temperature of −5 °C or 35 °C instead of room temperature and with the one-to-one method rather than performing a zonal taping. The most surprising result is the positive effect of storage at extreme temperatures but it remains a possibility that the effect is, in part at least, explained by between-roll differences in fibre recovery efficiency. The authors also highlight that the pliability and the propensity of the tape to tear can be important for the forensic tactics.

The same research team also studied and established a workflow for the use of the Easylift tape lifting system [51] for microplastic pollution monitoring which allows in situ analysis of fibres and other microparticles and is compatible with a wide range of non-destructive analytical techniques such as bright field microscopy, polarisation light, fluorescence light, microspectrophotometry, etc. Still in the context of microplastic pollution monitoring Prata et al. [52] state that there is a need of conducting quality control measures and blanks throughout the procedure of sampling, as airborne fibres are readily found in these control measures and with the use of field blanks prior to sampling it can be determined to see what the first source of contamination is and if there is a specific source that contributes to it. This conclusion could be extended to forensic fibre sampling.

An interesting workshop on 'Improving Forensic Trace Recovery' took place in February 2021. Due to the pandemic situation it was finally organised online. The workshop was informative about the European situation and various aspects were discussed such as trace recovery in complex cases, quality, R&D and training of crime scene operators. Similar crucial issues were detected among participants: crime scene assessment (no formal canvas; based on experience), dealing with multiple evidence recovery (at scene and in lab), implementing quality standards for crime scene management (procedures and assessment), crime scene practitioners (education, training and competency testing), crime scene reporting (collecting strategy and transparency), and harmonisation (need for best practice, SOP's or minimal requirement).

7. Instrumental methods

7.1. Automated fibre search

There were no new publications concerning automated fibre search which remains the most time-consuming step when searching for fibre traces on tape-lifts.

The SHUTTLE project [53] has already been mentioned in the previous review (Section: The Future). The SHUTTLE toolkit would provide an automated search and classification of microtraces on tape-lifts. Three contractors (consortium of providers) have been selected for proposing and designing a prototype (Phase 1). In Phase 2 contractors developed a first prototype based on the design documents delivered in Phase 1 and tested their solutions in lab conditions. During the ongoing Phase 3 the prototypes developed during the Phase 2 will be validated in operational environment to check their compliance with the requirements defined in the Tender Documentation.

7.2. Microscopy

Fibre analysis starts with microscopy. A fibre is examined through microscopy, typically at 200–400x magnitude and with different illumination conditions. In the period 2019–2021 an increased interest in this topic is observed in literature with several new publications that appeared.

De Wael published a book covering all aspects of microscopy in forensic fibre examination. The book is very fit for educational purposes and covers all different fibre types featuring many illustrations of the different characteristics observed when examining textile fibres with stereomicroscopy or optical light microscopy under different illuminations (bright field, polarized light and fluorescence) [8]. To quote James Robertson: "This book should be a must for any forensic organisation that purports to be serious about fibre examination and also for any individual who takes fibre examination seriously. It is not a book to simply place on the bookshelf and should be in everyday use. Beautifully illustrated, it has applications for training, and, to guide and to inform the development of examination protocols."

Bracker et al. compared the value, applicability and limitations of current USB microscopes with traditional microscopes [54]. USB microscopes provide inexpensive portable alternatives for imaging. They demonstrate different illumination options, a strong sensitivity to different hues but do not share the same level of resolution, image quality or image contrast as most sophisticated microscopes. At low magnifications they can add value to forensic investigations.

Another method for the identification of synthetic textile fibres using polarized light microscopy and based on quantitative measurements of the refractive indices is proposed by Reffner et al. [55] Compared to using PLM and regular measuring refractive index for fibre identification this new method is rapid, reduces remounting fibres in different mounting media and provides a quantitative measure for fibre comparisons.

It involves mounting a fiber in a mounting medium with a refractive index intermediate to the fibre's principal values, and determining an experimental angle of equality (corresponding to the orientation of the fibre with a minimum contrast) for comparing fibres.

A confocal microscope can also be used to identify cellulosic fibres (cotton, linen, rayon-viscose, ramie, jute) and plastic fibres by their morphological features [56].

In the context of archaeological studies Lukesova et al. conclude that cross-section shape and lumen shape cannot be used on their own as a distinct feature for plant fibre identification [57]. Proper identification is only possible by the combination of several methods, and even then, secure identification cannot always be ensured.

Zhu et al. gave a review of bicomponent fibres. [58]. They generally summarize the classification, structural characteristics, preparation methods and analytical methods to determine the dual component of the fibres. The review covers all aspects of bicomponent fibres and presents a useful document for fibre experts dealing with those kind of fibre traces.

7.3. Microspectrophotometry (MSP)

A review of the color analysis of textile fibres by microspectrophotometry is presented by Hu et al. [59] Besides an introduction to the principle of colour measurement by MSP and the discrimination power of the method, the increasing use of chemometrics and statistiscal methods is discussed in this review. This is confirmed by the new other contributions regarding MSP measurements. Rich et al. evaluate the performance of Lasso relative to principal component analysis (PCA) and linear discriminant analysis (LDA) using the Matlab software [60]. They measured over 700 donated fibres from various manufactures. The goal was to determine which wavelengths are critical in predicting the dye class of a given fibre sample. The authors found that Lasso outperformed combined PCA and LDA analysis.

Aitken et al. discuss the possibility to evaluate evidence for MSP data using functional data analysis [61]. Functional data analysis is the analysis of data in the form of functions. Functions can be represented by B-splines in the case of MSP data. The spectra are represented with linear functions comprised of piecewise quadratic characteristics with a limited number of coefficients. The technique is used for measurements on blue ink and red woollen and red cotton fibres and is found to be comparable in performance to conventional methods. Vergeer et al. have reacted to this publication by disputing some of the statements that were made in the paper [62]. In their opinion the values generated by this system cannot be interpreted as LRs as stated by Aitken et al. It should rather be seen as discriminating scores. A post-hoc calibrating step is necessary to transform the scores to well-calibrated LRs.

Killinger reports on the discrimination of colourless fibres by UV-VIS microspectrophotometry and microspectrofluorimetry [63]. In an extensive paper they show that MSP measurements on colourless fibres can be useful. They measured 88 round, colourless fibres including polyester, nylon, acrylic, rayon and olefin fibres with transmission and fluorescence measurements. The transmission measurements were taken with 10× objective, the emission spectra with 40× objective. The combined discrimination powers for polarized microscopy PLM, PLM + MSP transmission and PLM + MSP transmission + MSP emission were calculated. For transmission measurements, the discrimination was highest in the UV region. The authors also mention that the emission measurements are much more time-consuming compared to transmission spectra collection.

7.4. Raman and infrared spectroscopy

Both techniques are used in several ways to characterise textile dyes and fibres. Raman spectroscopy remains predominantly used for dye detection while infrared spectroscopy was used for both dye and polymer analysis.

Binary mixtures of textile dyes [64] were studied by Raman spectroscopy using two complementary laser sources, 514 nm and 785 nm respectively. The use of both lasers helped to overcome fluorescence issues and to increase dyes detection. The ability to detect both components in the mixture raised from 50% (one laser used) up to 70–75% when combining the use of both lasers.

Castro et al. [65] have chosen to extract azo dyes from polyester fibres prior to Raman analysis. This ensured a better detection of dyes in particular when using NIR lasers (e.g. 785 nm) that usually demonstrate a lower level of undesired fluorescence emission (but a higher contribution of the fibre polymer when measuring directly on the fibre).

Surface-enhanced Raman spectroscopy (SERS) may help to increase dye detection. A simple synthesis for SERS substrate [66] was proposed and suitably tested with eleven dyes selected from different chemical classes. The enhancement was stimulated by using a 473 nm laser line which is close to the absorption wavelength of the silver colloid. Puchowicz et al. [67] carried out SERS measurements directly on cotton fabrics dyed with reactive dyes. The pieces of fabric were dipped into the colloid solution and dried prior to analysis. The enhancement was found particularly useful with low colour intensity samples and especially when the dyes used reveal fluorescence emission with the chosen laser source.

Combining dye identification by Raman spectroscopy and historical data from dye manufacturing [68] may help for dating purposes. Although showing a stylistic aspect of the 15th century an historical silk carpet proved to be a late 19th or early 20th creation due to the use of synthetic dyes.

Peets et al. [69] studied a contactless way of identifying textile materials thanks to reflectance FTIR spectroscopy. Spectral comparison with data collected by ATR-FTIR techniques is complicated due to band shifts and broadening, as well as changes in intensity and band ratios. However, the reflectance spectra allowed to reach comparable performance for discrimination purposes and seem to be more informative for differentiating amid-based fibres.

Metal underlayer ATR-FTIR methodology [70] is combining the detection ability of the ATR technique and the separation of dye constituents on a gold-coated TLC plate. The methodology reduces the fibre matrix interference and thus improves the identification of synthetic dyes, even in small amounts.

Lavine et al. [71] reviewed the literature of the past ten years related to the comparison of infrared spectra. They discuss the two main approaches based on library searches on one hand and on the other hand, on pattern recognition for discrimination or classification purposes.

7.5. Chromatography

Two extensive reviews appeared covering the identification by chromatographic and spectroscopic methods of polyester fibres dyed with disperse dyes and cotton fibres dyes with reactive dyes [72,73]. Both reviews discuss the different type of dyes and give an overview of the extraction procedures for isolation as well as the chromatographic methods described in the literature for the identification of reactive dyes extracted from cotton and disperse dyes extracted from polyester fibres and discuss the detection and analysis of dyes by the use of microspectrophotometry and Raman spectroscopy.

Smigiel-Kaminsky et al. developed and validated two HPLC-DAD and one UPLC-QTOF-MS methods for identifying disperse dyes in single polyester fibres [74]. Different extraction agents were tested and chlorobenzene was found to be the most effective.

Gora et al. confirm the use of thin layer chromatography TLC for differentiation of dyes after an enzymatic extraction from cotton fibres [75]. They chose 21 red cotton samples and coupled the visualisation with video spectral comparator (VSC). They found this technique to be more effective in differentiation of red cotton fibres than the optical light microscopy, MSP and Raman.

7.6. Emerging techniques

Amin et al. propose using Au–TiO_2 nanohybrids for the forensic analysis of dyes in fibres with surface-assisted pulsed laser desorption ionization-mass spectrometry (SALDI-MS) [76]. They analysed dyed polyester fibres coated with these nanohybrids and found that the detection sensitivity of the dyes is enhanced.

An interesting study was performed by Dolan et al. where they were able to detect and differentiate fluorinated surface treatments on single fibres by the use of pyrolysis-gas chromatography–mass spectrometry (py-GC-MS) combined with a new elemental ionization source: plasma-assisted reaction chemical ionization (PARCI) [77]. The authors provide good background information with respect to the use and detection of fluorinated coatings on fibres and analysed pre-coated fabric samples as well as fibres with coating applied in their lab. Challenges were encountered only for 3 out of 22 samples. In another publication Dolan et al. also demonstrate that fluorinated coating were successfully detected on the single-fibre level with py-GC-PARCI-MS for all 9 examined clothing items with oil- and water-repellent properties, also distinguishing clusters of at least three different detectable classes [78].

Komatsu et al. discriminate 8 types of red silk fibres with non-destructive total reflection X-ray fluorescence (TXRF) and synchrotron radiation X-ray fluorescence (SR-XRF) spectrometry based on the presence of Cr and Zn (TXRF) and Cr, Co, Zn, and Br (SR-XRF) as well as the Zn/Cr signal intensity ratios [79]. In their opinion SEM-EDS is often unsuitable for detecting trace elements in silk fibres and involves a destructive technique. Another application for synchrotron radiation microbeam X-ray fluorescence spectrometry (SR-μ-XRF) is described in a paper by Nishiwaki et al. where the authors were able to discriminate single white polyester fibres based on the identification of elements originating from catalysts [80].

Alternatives for fibre identification are mentioned by Liang et al. in the use of thermal desorption/pyrolysis-direct analysis in real time-mass spectrometry (TD/Py-DART-MS) for the identification of fibres [81], Zhou et al. in discussing the possibility to identify textile fibres with near-infrared spectroscopy and pattern recognition. [82] and Zughaibi et al. by the use of Direct Analysis in Real Time Coupled (DART) coupled to an accurate time-of-flight (AccuTOF) mass spectrometer (MS) and where they were able to correctly identify 22 carpet samples [83].

8. Quality aspects

The European Network of Forensic Science Institutes (ENFSI) has initiated the renewing of the Best Practice Manuals in several disciplines [84]. Some BPMs were already existing in various formats and the new ones will be published using a common official template. Thanks to European direct grants the AFORE project (Work Package 5) has started in 2020 and several teams have worked on the production of new and updated BPMs (dedicated to 1. Digital Image Authentication, 2. Examination of Fibres, 3. Examination of gunshot residues (GSR), 4. Handwriting Examination, 5. Voice Comparison, 6. Human Forensic DNA Profiling, 7. Examination of Glass). Due to the pandemic situation most of the accomplished work in 2020–2021 has been done remotely but nevertheless successfully. During this period the existing fibre BPM has been refreshed using the new ENFSI template and updated. Extra material has also been converted into several appendices. Then the BPM draft document has been submitted to the forensic community for peer-reviewing in different subsequent ways: a first private commenting round by e-mail, an online workshop with breakout group discussions, and a second public commenting round based on the final draft posted on the ENFSI website. A final draft was already available at the end of 2021 and submitted to the ENFSI board for official publication on the website. The pandemic situation revealed that working groups are able to work efficiently using the online communication tools. This clearly highlights new possibilities for the future production of manuals, guidelines and other standard documents. This way of working deserves to be encouraged but should not fully replace physical meetings that ensure the cohesion of the working group.

Training is also an important aspect of quality assurance. Already mentioned in the previous Interpol review the ENFSI ETHG e-learning platform for forensic hair and fibre practitioners was released in December 2020 and is open for registration [85]. Over 150 users have already registered. This e-learning project was coordinated by members of the European Fibre and Hair Group ETHG and was the main part of the work package G5 ″Development of a Training and Education Concept for Forensic Hair and Fibre Experts" which is funded by the 2016 Direct Grant of the European Union to ENFSI. The aim of this e-learning environment is to provide the ETHG community with a unified training program that is remotely accessible, in order to support practitioners and their institutes in education and training efforts. The tool is very interactive and covers key processes of forensic hair and fibre examination. A workshop was organized in Prague in September 2019 to present and validate the content of the platform to and by a selected group of members of the ETHG community with different levels of experience and from different countries. More than 35 e-learning modules and other training activities are available in four different courses, depending on individual training needs: (1) From the Crime Scene to the Laboratory: case assessment, packaging and documentation, recovery methods, anti-contamination and sampling strategies; (2) Microscopy: fundamental concepts of the important microscopic techniques as well as guidance and tools for the discrimination, identification and comparison of fibres and hairs; (3) Microspectrophotometry (MSP): fundamental concepts, sampling and analysis and interpretation of spectra; (4) FTIR: fundamental concepts and sample preparation. Thanks to a new direct grant the actual package will be expanded in the future, more modules and activities are in construction, more specifically with regard to the topics of Evaluative Reporting and Interpretation, Textile Damage and Raman spectroscopy. The ETHG e-learning platform is open to ETHG members, associates and guests free of charge.

9. Textile industry/new fibres

New developments in the textile industry follow the trends exposed in the previous Interpol review [1]. General information and internet links on textile production and new products can also be found in that review.

The 5th International Conference on Natural Fibres took place online in 2021. This is a scientific and technical conference on the new developments in the field of natural fibres used for textile or composite materials. Most of the presentations were focused on the technical processes and/or the determination of mechanical or physical properties of these materials. Lecturers are mostly academic or they work in research centres dedicated to textile or composite materials. They are often associated with industrial partners in research projects with (inter) national funding. The content does not really match with the routine work of a forensic practitioner. Nevertheless, the conference can provide some informative content about industrial processes and testing of textile materials, as well as new developments in the use of natural fibres on the market. Only a few presentations concerned the microscopic aspects of textile fibres but they are more oriented on the determination of the fibre length and diameter. These parameters have less interest for forensic examination in the case of natural fibres.

10. Knots and ropes analysis

Over the last reviews the major contributor of this section was usually Chisnall who is contributing again with two articles. The first one on analysing knots and ligatures [86] describes different knots through their qualitative and quantitative characteristics beyond the fundamental task of correctly identifying and documenting knots and ligatures. The article gives a comprehensive introduction of usual knots and tying principles that provides a didactic summary for newbies or a refreshing reading for occasional practitioners. The knot characteristics and structural changes sections are rather dedicated to specialised practitioners. Besides well-known (in)consistency in chirality self-tying can be challenging when confronting autoerotic fatalities, suicides, and suicides staged as homicides. In addition a tier can chose to use one or both wends or might have folded the rope in half, requiring careful examination to reveal the tying method and/or sequence. Nevertheless, the simplest knots remain used repeatedly and knots indicating any level of skill or training have been noted in only 5% of cases and surveys. When comparing knots practitioners are interested in invariant characteristics that cannot change regardless of how knots are manipulated or distorted. One perspective is to reduce complex knots (especially those that are too tangled to identify) to a minimum number of crossing points; the resulting crossing number being a basic quantitative knot invariant. This characteristic is however insufficient for indicating whether knots are different or equal and needs to be combined with other intrinsic features of the knot. Writhe and linking number are other invariants using a crossing orientation topological procedure. Simple invariants might help in some instances even if knots can usually be distinguished by careful examination, knot drawings and precise reconstruction in secondary materials. Another potentially informative physical attribute is the sinuosity which represents the amount of rope contained within a knot. Without untying the questioned knot the sinuosity can be assessed by tying a control sample using an identical material. This procedure is challenging and will be difficult in case of contaminated samples (e.g. rope saturated with blood). Sinuosity and crossing number will determine the concatenation (a qualitative feature of knot entanglement and strength). The last section of the article also describes how knots can undergo structural changes, deliberately or by accident. A knot may thus be transformed by several means into something that is structurally similar or different. Capsizing and flipping are the most common ways and can occur accidently when securing evidence. The other changing actions described by Chisnall are more prone to be deliberate. Implementing evaluative procedures to forensic knot analysis will rely on appreciation for qualitative and quantitative knot characteristics, and how knots may change.

The second article [87] proposes a comparative analysis of casework and survey data on the distinguishing between homicide and suicide knots and ligatures. The latter being challenging since homicides may be staged as suicides to divert guilt, while suicides can be disguised as homicides to implicate someone else. Previous literature mainly suggests a reversal of the chirality during the self-tying compared to the external tying process. Data from casework highlight that fixed knots are prevalent in external tying cases, while sliding knots mostly appeared in self-tying cases. A significant indicator of self-tying is the relative looseness of the ligatures with knots tied in a location accessible to the victim. Knots from self-tying cases are unsophisticated while sophisticated knots are well observed (in less than 5% of cases) for external tying. A major finding from the survey data is that self-tied ligatures are typically loose, and demonstrate noticeable wrist gaps. Another interesting result is that self-tying lead to a chirality reversal for some tiers but not all; S tiers being more prone to reverse chirality (twice as often as natural Z tiers). The main achievement of this study is the conception of a checklist establishing some contrasting characteristics between external and self-tying which may help to assess how the tying was performed.

Cordner et al. [88] have produced an extensive review on suicidal ligature strangulation. The study excludes accidental strangulation and autoerotic fatalities, but includes the involvement of any weights or devices to facilitate the strangulation, except the body weight itself (hanging scenario). This review has identified and synthesized the evidence from 31 case reports of suicidal ligature strangulation. Various types of ligature (e.g. string, rope, panty-hose, scarf, belt, tie, rubber band, etc.) were observed. Regarding the presence of knots on the ligature the number of knots was reported as none in 12 cases, one knot in 7 cases and more than one knot in 9 cases. The position of the knot (or the position in relation to each other in case of several knots) around the neck was variable. In each case it appeared that there was a means by which pressure would be maintained on the neck after consciousness was lost. Other medico-legal observations and toxicology results are also presented. This study suffered from the lack of homogeneity in the reported details and from the variable terminology used. The terminology and criteria mentioned in the review can potentially help to strengthen and standardise upcoming case reporting and improve the basis for a future systematic review.

Benevento et al. [89] describe a case with a complex suicide by drowning and self-strangulation. The victim has committed suicide by throwing himself into the sea after tying a large stone with a rope (triple bowline knot) and tying the other end with a slipknot around his neck. Regarding knot analysis the used knots are however briefly described. As long as the stone was not touching the bottom, a strangulation process could have been effective even in water. The death could thus be attributed to the unusual combination of both drowning and self-strangulation.

11. Evidence interpretation

There is an increasing interest in discussing the way of reporting forensic evidence and witnessing in Court. In the past evidence interpretation was often mixed up with Bayesian evaluation but the latter is one (among others) possible way of drawing conclusions or giving an expert's opinion. The scope of evidence interpretation is only to provide an intelligible way of explaining scientific results to the judicial system (magistrates, police officers, lawyers, judges or jury in Court). The observed trend over the past years is not to definitely choose one manner against the others, but rather to standardise or harmonise the writing of conclusions within a country (e.g. US, Germany) or within a forensic network (e.g. ENFSI guideline for evaluative reporting, OSAC standards).

11.1. Dedicated to fibre examination

No standard for fibre evidence interpretation was published and the debate on how to harmonise/standardise is still active. However, two publications were found to contribute to the use of a Bayesian approach for the interpretation of fibre results. The first one is focused on the source level and the use of relevant data; the second one discusses the activity level.

De Zwart and van der Weerd [31] proposed a methodology to filter the contents of a database such that only items that are considered relevant are selected. They also discussed the formulation of source level propositions (Bayesian reasoning) depending on the prior information available. Formation of a suitable dataset may be challenging, as relevant population varies from case to case. The authors suggest to compile a broad and generic database, that can be filtered using a SQL code to extract the relevant population. In particular colour is considered relevant in many cases and may result from both preliminary investigations or prior information (e.g. video images, witnessing). Forensic examiners might be reluctant to include contextual information (i.e. witnessing) into their evaluation, but limiting the relevant population to a particular colour circumvents this problem by solely considering analytical results obtained in the laboratory. Indeed fibre traces were categorised by a defined colour and the search for a putative source in the suspect's environment was based on that colour. When all textile colours are used for evaluation, it would be advisable to filter data that are only related to case samples into the relevant population. Otherwise, data from some particular R&D projects could introduce a bias because the extracted set is not representative for the general population. In the case of macroscopically visible characteristics (e.g. rope comparison) the police would not submit an item with discernible characteristics for comparison purposes. This results in an ambiguous specification of the relevant population and cannot be used to define a database query unambiguously. Characteristics used to define the relevant population must be specified unambiguously in order to implement an adequate filter, but the outcome of various database searches (different filters) may also assist an examiner in monitoring the effects of different definitions of the relevant population on the evidential value and on the subsequent evaluative reasoning.

Taroni, Garbolino and Aitken [90] developed a generalised Bayes factor formula and an associated Bayesian network for the transfer of fibre traces under activity level propositions. Three narrative examples were used to illustrate the possible calculations and how the value of the Bayes factor may increase or not. Examples depict real case scenario where the victim and the person of interest may be close friends/relatives, have friends in common or are strangers without any connection. The numerical examples suggest that the possible existence of an alternative transfer mechanism (a secondary/third party transfer) plays the main role (under both prosecutor and defence propositions) in the quantification of the value of the evidence. Values for the population characteristics are less important in the assessment of the Bayes factor under activity propositions than under source propositions.

11.2. More general considerations

As a consequence of the PCAST report on forensic science in 2016 there is a global debate on expert reporting and testimony in Court. Ten studies from Europe (1), the USA (2) and especially Australia (7) contributed to apprehend the statement and the perceptions of expert conclusions and opinion.

An Australian study [91,92] investigated the reporting practices of forensic scientists using the reported results of the 2016 CTS forensic tests (500 randomly selected responses; 8 different disciplines including fibres). Categorical statements (e.g. match, identification, elimination) was by far the most prevalent conclusion type observed (73.8% of conclusions). The provision of some reasoning or justification for the final conclusion was the most prevalent additional content type (46.2% of conclusions). Information about reliability and validity was rarely reported. This is likely to leave their intended audiences – legal decision-makers with limited scientific training – in a position where they may significantly overvalue the evidence. Another American study [93] sought to measure the extent of probabilistic reporting (single LR or range of plausible LR) in forensic science in the USA. This kind of reporting appeared very infrequently in the four forensic disciplines studied. Most reports generally adhered to prevailing practitioner standards. The reports were usually categorical and the notorious “match” and “consistent with” expressions appeared frequently. The relatively few probabilistic reports found were almost entirely “inconclusive”.

Reid & Howes [94] explored the presentation of forensic reports and corresponding testimony in major crime against the person. Expert reports were found brief and omitted much of the detail recommended to allow the reader a greater understanding of the evidence. Oppositely testimony provided opportunities for forensic scientists to elaborate on their findings and expert opinion.

A risk management framework [95] was used to assess the potential impact of bias on forensic interpretations across multiple disciplines within a forensic institute. Participants with various levels of expertise were first informed about relevant literature, recommendations and guidelines relating to mitigating the impact of cognitive bias in forensic science. Thirty-two risks were identified among which ten were applied across multiple disciplines; the remaining ones being relevant to individual disciplines. The risks described were found to fall into two distinct categories: ‘favouring one party over another’ (bias might influence selection decisions but not interpretation of subsequent analytical results) or ‘contribute to a miscarriage of justice’ (impact to result/interpretation used as evidence in Court). Different recommendations are suggested for raising awareness of cognitive bias, limiting access to task irrelevant information and reducing expectation bias (multidiscipline or connected experts). This risk assessment may not be directly applicable to other forensic science organisations for some particular aspects of the authors' institution.

Van Stralen et al. [96] studied the interpretation of forensic conclusions by criminal justice professionals (N = 269). Three types of conclusions with various levels of strength were assessed by the participants: categorical, verbal or numerical likelihood ratios. Participants seemed to overestimate the strength of almost all conclusion types and phrasings. A categorical phrasing was usually best understood for a weak conclusion and a verbal LR conclusion was best understood with a strong strength. When comparing the three types of conclusions the categorical conclusion seemed to be misinterpreted the most.

A didactic review written by Eldridge [97] made the state of the art of juror comprehension of forensic expert testimony. This review also includes the discussion of various evidence presentation methods by experts and the perceptions of credibility by jurors. Regarding the latter the pre-existing beliefs (i.e. jurors' prior beliefs and perceptions in Court) about forensic science [98] were investigated at specific stages through the forensic science process. Surprisingly, participants (N = 101) did not blindly consider that all forensic techniques are highly accurate (CSI effect) but believed that there was a substantial likelihood of error and a considerable human judgement at each stage of the forensic process. These beliefs may partly be a result of the sequencing of the forensic process for the purpose of the survey. The accuracy of forensic techniques was estimated to range from approximately 65% (document analysis) up to 90% (DNA), where materials evidence received a value of 79%. A similar study about the reliability of forensic science evidence [99] was conducted on two groups of participants, lay people (N = 1061) and forensic practitioners (N = 53). There was a considerable agreement between practitioners and lay people that forensic evidence is reliable. DNA and fingerprints were consistently viewed as the most reliable forms of evidence (85–89%) while the least reliable was scored approximately 55%. Fibre comparison and trace evidence were ranked intermediate with a 60–70% reliability.

Woodman et al. [100] first studied the impact of chemical trace evidence on justice outcomes. Chemical trace evidence was found to be utilised for supporting the progress of high level crime cases through the criminal justice system. Oppositely to DNA analysis chemical trace examinations cannot be considered as a standalone predictor for judicial outcomes. But Court outcomes are expected when chemical traces are associated with other forensic and non-forensic evidence. A second study [101] involving a selection of lead investigators in criminal investigations focused on the impact of chemical trace evidence on how the cases progress through the criminal judicial system. For most of the respondents chemical trace evidence is used for building the case for Court and for establishing a nexus between suspects and a crime. Complementarily to identification evidence chemical traces were associated with providing information helping in the reconstruction of the crime. The survey findings add support to applying a holistic approach to the management of cases rather than considering which discipline is likely to provide the highest utility. In a large majority of the survey cases investigators received verbally some preliminary results prior to the formal written reports, enabling chemical trace evidence to contribute timely to investigations. The findings suggest that formal written reports (containing additional critical information about chain of custody, expert's qualifications, quality aspects and verbal scales of conclusions) may not be fit for purpose for the investigators, but more appropriate for use in Court.

12. The future

An online survey [102] was disseminated to forensic practitioners and researchers worldwide (544 participants from more than 20 countries). Overall participants supported development of objective methodologies, validation and further investigation into the application of statistics, use of error rates and implications of cognitive bias. The development of objective methods should continue despite no consensus among respondents reached if forensic methods are mostly subjective or objective. In particular validation continues to be raised as an issue and few validation studies have been published for several disciplines. The latter is supported by the lack of resources in the 'Quality' section of the past and present Interpol reviews.

The importance of databases was already discussed in the same section of the previous Interpol review [1] and their use was also discussed in terms of evidential value estimation (Section: Significance of evidence). Klaasse et al. [103] reported the construction of a new kind of multidisciplinary database, named TraceBase. The database was designed such that data from several sources, different forensic disciplines and data acquired by different analytical techniques can be entered. When necessary a sub-collection of data can be filtered for a specific use. Setting-up robust, useable and user-friendly databases is time-consuming and a complex task that may be performed more efficiently when centralised as a general database hosting several data collections.

Several publications noted and discussed the increasing fragmentation of forensic science into separate processes and specialisations. Some issues may raise from this phenomenon and proposed solutions to solve one problem may also lead to other issues in other parts of the process.

San Pietro et al. [104] discussed some consequences of both the increasing specialisation of forensic scientists and sophistication of analytical capabilities over the last years. Higher education and mentoring by experienced scientists are key factors for the creation of the next generation of criminalists. Increased specialisation and accreditation mostly benefit to the "how" to carry out the examination, but "why" it is being done is also critical. A general forensic approach should remain the basic of forensic science education. Other authors [105] suggested to redefine forensic science as a distinct discipline based on studying traces: "how", "when" and "where" the material transfer took place. This approach will also foster the development of a forensic science culture (instead of a primarily technological culture) unified by purpose rather than means.

The combined effect of the strong specialisation of forensic disciplines and the reduction of the operating funds [106] led to the decrease of the number of competent forensic practitioners per lab to a few or even to a single person per discipline. This is causing some operational issues, particularly on the service continuity and the reporting delay. By analogy with the way of working of the metrological laboratories the authors proposed a new model based on international collaboration and outsourcing to external public and private partners. It requires an openness of mind in the management of forensic laboratories but also to address some legal issues (different legal systems, languages, ways of reporting or giving an expert opinion, and of course the transfer of evidence materials, etc.).

Weyermann and Roux [107] compared forensic science with established disciplines, namely material science, medicine and historical science. A key to address current and future challenges is a balance between the unifying of forensic concepts and principles focused on the trace(s), an appropriate reasoning and the flexibility to adapt to a large variety of purposes in different politico-legal systems. The authors suggested that issues in the first stages of the process (i.e., crime scene investigation) should be addressed in priority for subsequent stages to function correctly.

The future of forensic science should of course respond to some past critics about a potential lack of objectivity by addressing some quality issues, but this particular discipline cannot fully reproduce the models proposed by pure or applied sciences. The process of forensic science is indeed very complex from crime scene to Court and refocusing on a "trace" approach could effectively be a path forward for the discipline.

13. Summary

The amount of publications related to forensic fibre examinations has quite doubled in the period 2019–2022 compared to the previous period 2016–2019. This increase is highlighting the prolific activity of the forensic fibre and textile community across the world and especially in Europe, UK, USA, Canada and Australia. To some extent the observed boost for publishing may be a collateral effect of the pandemic situation which has temporary slowed down the forensic workload (or teaching for academics) and promoted homeworking. In any way the present review shows that fibre practitioners took time to publish their research data on various topics or to write down some opinion about best practices, evidence interpretation and the future of forensic science.

Again a lot of the research was dedicated to transfer and persistence studies as well as other studies contributing to the significance of fibre evidence. The development and use of databases seem to be of major interest for both compiling useful analytical data and extracting statistical frequencies of occurrence. All these studies and databases are crucial for interpreting fibre evidence and reporting valuable conclusions. The way of reporting is also a major concern even beyond the field of fibre and textile examination.

The interest in the field of textile damage analysis is still growing with several studies at both textile and fibre levels. Damage examination remains a popular and entire discipline besides fibre examination.

Technical publications about analytical instrumentation are becoming fewer over the years and the interest seems to have shifted to data processing using for instance chemometrics as depicted in the MSP section of this review.

In contrast to other forensic disciplines the QA section of the review is once again very limited due to a lack of publications in this field. To the author's knowledge more and more forensic institutes are now accredited but few are sharing their methodologies and validations. However, a new Best Practice Manual for the examination of fibres is published by ENFSI highlighting the awareness of the community for standards and quality.

Thanks to a great effort within the European Textile and Hair Group (ENFSI/ETHG) the future trend towards harmonisation and standardisation can rely on an e-learning platform with harmonized and widely-supported courses for the fibre and hair community. The training of new practitioners is indeed the first important step in reaching harmonized best practices as mentioned by many authors throughout the forensic literature.

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