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# Interpol questioned documents review 2019–2022

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## 1. Introduction

The goal of this paper is to provide a comprehensive review of the technical advances and general areas of research in the field of Forensic Handwriting/Forensic Document Examination since the 19th INTERPOL International Forensic Sciences Management Symposium in 2019. This review is based on articles published in major forensic and generalist science journals, as well as books, and presentations at international forensic meetings during the period 2019 until mid-year 2022.

While the main goal of this review is to gather all useful and relevant elements for the improvement or even implementation of a questioned documents forensic laboratory, it also aims to help laboratories in choosing direction for new initiatives and internal developments, and to facilitate their capability development with respect to instrumentation and technology.

It has been noted anecdotally that many crime laboratories have shuttered their FDE Sections in recent years, however, as can be seen from the plethora of ongoing research in this field, this trend is not global. In fact, for many crimes, such as financial and economic crimes, identity-based crimes, and national security, forensic handwriting/document examination is key to resolution. To expand on this, forensic document examination is a field that is not well understood even within the broader, modern forensic community. For example, while the definition of a document to some is quite narrow - a piece of paper with some printed text – forensic document examiners consider a much broader definition: any support used to transmit a message, such as paper, cardboard, plastic, concrete (graffiti), mirrors, white or blackboards, and all the components used to make that document.

Further, in FDE the questions posed typically require multiple examination types to properly respond to the many different questions about occurrences, origin, and production of those documents. In essence, FDEs are asked to determine the who, what, where, when, and how of documents. Determining authorship of handwriting provides the who. Concluding about the production of documents such as process determination, instrument make-and-model determination, date of production assessments, association of suspect devices and counterfeit assessments respond to what, when, and where. And establishing occurrences to documents – such as what has happened before, during and after production, erasures, alterations, and obliterations all respond to the how, and possibly to the why.

Given that this discipline is so broad and the different areas of analysis within the field so numerous, the results of the bibliographic research are grouped into key topics as follows: Forensic Handwriting Examination, Forensic Document Examination, Forensic Intelligence, Quality Assurance, Miscellaneous, and Trends, Challenges and Gaps. Several of these categories are further divided into subject areas. The Forensic Handwriting Examination section is divided into the following sections: Offline Signatures/Handwriting, Digitally Captured Signatures/Handwriting, Automated Systems, and Indentation Development. The Forensic Document Examination section is subdivided into the following categories: Equipment Advances and Updates, Writing Instruments and Ink, Printing Technologies, Stamps and Stamp Inks, Substrates, Document Dating, Document Recovery (which is further divided into Alterations and Obliterations, Charred and Fluid-Soaked, and Reconstruction), Digital Documents, and Security Documents Examination. The Quality Assurance section also has subcategories: Human Factors and Cognitive Bias, Validity and the Courts, and Standards and Best Practices.

There were many references found (21 textbooks, 450 published papers, 543 conference presentations, which includes workshops) and from a wide variety of sources, due to the authors' inclusion of articles and presentations from non-standard sources as well as from online conferences.

Although every effort has been made to ensure all developments in forensic handwriting/document examination have been covered in this review, some omissions are possible. It is important to underscore that the scientific basis of all papers and presentations are not validated by the authors of this review.

## 2. Sources of reference

References presented in this work and listed below, come either from the scientific literature (forensic or not), or publications from various international meetings.

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### 2.1. Specialised references in forensic science

- Australian Journal of Forensic Sciences
- Brazilian Journal of Forensic Sciences
- Egyptian Journal of Forensic Sciences
- ForensicAsia
- Forensic Chemistry
- Forensic Science & Criminology
- Forensic Science International
- Forensic Science Research
- Journal of the Canadian Society of Forensic Science
- Journal of Forensic Sciences
- Journal of Forensic Science and Medicine
- Journal of the American Society of Questioned Document Examiners
- Problems in Forensic Sciences
- Science & Justice
- Themis: Research Journal of Justice Studies and Forensic Science
- Theory and Practice of Forensic Science
- Turkish Journal of Forensic Sciences

### 2.2. Other references

- American Journal of Neural Networks and Applications
- Analyst
- Analytica Chimica Acta
- Analytical and Bioanalytical Chemistry
- Analytical Chemistry
- Analytical Letters
- Analytical Methods
- Annals of Medicine
- Applied Intelligence
- Applied Materials Today
- Applied Sciences
- Arab Journal of Nuclear Sciences and Applications
- Arch Neuropsychiatry
- arXiv
- Chemical Papers
- Chemometrics and Intelligent Laboratory Systems
- Cognition
- Cognitive Computation
- Computers & Security
- Egyptian Journal of Chemistry
- Electronics
- European Physical Journal Plus
- Expert Systems with Applications
- Global Challenges
- Heritage Science
- Human Brain Mapping
- IEEE Access
- IEEE Journal of Biomedical and Health Informatics
- IEEE Latin America Transactions
- IEEE Reviews in Biomedical Engineering
- IEEE Sensors Journal
- IEEE Signal Processing Letters
- IEEE Transactions on Biometrics, Behavior, and Identity Science
- IEEE Transactions on Haptics
- IEEE Transactions on Information Forensics and Security
- IEEE Transactions on Instrumentation and Measurement
- IEEE Transactions on Mobile Computing
- IEEE Transactions on Multimedia
- IEEE Transactions on Neural Networks and Learning Systems
- IEEE Transactions on Pattern Analysis and Machine Intelligence
- IEEE Transactions On Systems, Man, and Cybernetics: Systems
- IET Biometrics
- IET Image Processing
- Information Processing & Management
- International Journal of Analytical Chemistry
- International Journal of Computer and Information Engineering
- International Journal of Emerging Technologies
- International Journal of Engineering and Advanced Technology (IJEAT)
- International Journal of Engineering Trends and Technology
- International Journal of Science and Research
- International Journal of Medical Toxicology and Legal Medicine
- Journal of Ambient Intelligence and Humanizing Computing
- Journal of Analytical and Applied Pyrolysis
- Journal of Analytical Chemistry
- Journal of Analytical Methods in Chemistry
- Journal of Architecture, Engineering & Fine Arts
- Journal of Clinical Neuroscience
- Journal of Cultural Heritage
- Journal of Imaging Science and Technology
- Journal of Information Security and Applications
- Journal of Molecular Structure
- Journal of Physics
- Journal of Raman Spectroscopy
- Journal of Seybold Report
- Kobe Journal of Medical Sciences
- Laser Physics Letters
- Materials Today Chemistry
- Microchemical Journal
- Molecules
- Movement Disorders Clinical Practice
- Multimedia Tools and Applications
- Neuropsychopharmacology reports
- Nowa Kodyfikacja Prawa Karnego
- npj Science of Learning - Nature
- Optical Engineering
- Optik
- Paedagogica Historica
- Pattern Recognition Letters
- PloS one
- Przegląd Prawa i Administracji
- Procedia Computer Science
- Quimica Nova
- Radiocarbon
- Reading and Writing - An Interdisciplinary Journal
- Science Advances
- Scientific Reports Nature Research
- Sensors
- Signal Processing-Image Communication
- Soft Computing
- Spectrochimica Acta Part a-Molecular and Biomolecular Spectroscopy
- Spectroscopy Letters
- Statistical Analysis and Data Mining
- Talanta
- TRaC Trends in Analytical Chemistry
- Trends in Analytical Chemistry
- Vibrational Spectroscopy
- Guang Pu Xue Yu Guang Pu Fen Xi/Spectroscopy and Spectral Analysis

### 2.3. Meeting, symposium, forums

- 10th IEEE International Conference on Communication, Networks and Satellite, Comnetsat 2021
- ACM Symposium on Document Engineering
- American Academy of Forensic Sciences
- American Society of Questioned Document Examiners
- American Society for Mass Spectrometry Conference 2019
- Australasian Society of Forensic Document Examiners, Inc.

- Canadian Society of Forensic Science
- Congress and General Assembly of the International Union of Crystallography
- CSAFE Webinars
- Digital Document Security Conference
- European Document Examiners Working Group
- European Network of Forensic Handwriting Examiners
- Evaluative Reporting Symposium
- High Security Printing Asia
- High Security Printing EMEA
- High Security Printing Europe, Middle East and Africa Conference
- High Security Printing Latin America
- IAI International Educational Conference
- IEEE International Conference on Image Processing
- IEEE International Conference on Multimedia and Expo
- International Association for Identification - Annual Educational Conference
- International Conference on Analytical and Bioanalytical Chemistry (ICABC)
- International Conference on Document Analysis and Recognition
- International Conference on Frontiers in Handwriting Recognition
- International Conference on Pattern Recognition Application and Methods
- National Forensic Science Symposium
- Optical Document Security Conference

## 3. Forensic handwriting examination

This section is broken in four subsections as follows: offline, digitally captured signatures/handwriting, automated systems, and indentation development. Offline is the term used to describe handwriting and signatures in an analog sense, that is, ink (or other writing instrument) on paper (or other substrate). The topic of digitally captured handwriting has exploded over the past few years and deserves separate treatment in this review. Automated systems, while not novel, has its place in this review as this subject is of relevance to forensics. Lastly, indentation development is included in this section on forensic handwriting examination as predominantly indentation development reveals latent handwritten impressions.

### 3.1. Offline

In this subsection are highlights of the two textbooks published during the period under review, and the 72 articles published dealing with handwriting identification and examination, including research into handwriting education which provides important context and background to the FDE. As well, there were 51 presentations given at the various forensic conferences during this time.

Two textbooks were published during the review period specifically about forensic handwriting examination. Mohammed compiled Forensic Examination of Signatures, a comprehensive work that explains the neuroscience and kinematics of signature production, giving specific details of research conducted on the topic. It provides practical details for forensic examiners to consider when examining signatures, especially in this era of increasing digital signature usage. Written by a foremost forensic document examiner, this reference provides forensic handwriting examiners, the legal community, the judiciary, and the academic community with a comprehensive record of the state-of-the-art of signature examination and plans for addressing future research into improving the reliability of the field [1].

Morris wrote a modern text on the fundamental concepts and principles of handwriting identification [2]. This text is aimed towards law enforcement and legal communities, and teaches how to interpret an examiner's report, the significance of various handwriting opinions and the influencing factors which must be considered.

#### 3.1.1. Handwriting examination

Tan et al. investigated the cross-language relationship between Chinese Hanzi and Latin script handwriting systems in the Chinese community of the Klang Valley [3]. Their study indicated that there is some correspondence in the handwriting of an individual when using two different language systems.

A new method for measuring pen pressure of handwriting was proposed by Negrini Neto et al. The analysis of handwritten documents through a system composed of a pre-selector optical analyzer equipped with light sources of different wavelengths coupled with bandpass filters combined with an optical coherence tomography instrument was described. With this substrate-independent methodology, the authors assert that it is possible to identify similarities, or differences, between the pieces of evidence under investigation, increasing the possibility of correct attribution concerning the authorship [4].

Guo and Li conducted a pilot study on the effects on pen pressure of the holding position of the pen. They collected several handwriting samples of Chinese characters and utilized the 3D property of stroke indentation to explore how pen strokes left on the paper can assist with forensic investigation [5]. The authors found that they could tell with a great degree of certainty whether the sample was formed with a left-hand or right-hand writer and how the pen was being held.

By their research project, Guo and Jia [6] attempt to detect forgeries and identify the forger by studying forgers' techniques description combined with eye movement tracking studies. This first step of the research demonstrates, by using the event-related potential technique, that forgers experienced more difficulty identifying their own forgeries than genuine exemplars. The suggested hypothesis is that the imitators have more difficulties as the forgeries include not only features they have consciously copied, but also some of their own handwriting traits that they could not successfully suppress during the attempted forgery.

By identifying the key points in handwriting and clustering the patches around these key points to generate an implicit shape codebook, Bennour et al. [7] characterized writer from handwriting and reported good identification performance.

In their research, Fuglsby et al. [8] studied the relationship between two automated handwriting identification systems. The first system uses measurements extracted from a static image of handwriting while the other uses kinematic features from pen strokes. The dissimilarities between pairs of samples were calculated for each system. The results showed that relationships existed for kinematic spatial-geometric pen stroke features and graph-based features, as well as for temporal feature, but not for pen pressure.

Kang et al. [9] studied the error rates in Korean handwriting examination performed by a forensic document examiners (FDE) group and a non-experts group. As expected, the error rates are less important for FDE group than for non-expert group. However, FDE gave more "inconclusive opinion", and the error rates is more important when the handwriting samples were simulated or disguised. Another part of the study demonstrated that the peer review is important to reduce the error rates. The study also demonstrated financial reward affect the results for the non-expert group.

Marcinowski [10] created a novel top interpretable neural network (TINN) for identification of the authors of handwritten documents. The features extracted included 80 binary features of handwriting and four binary categories of handwriting. The results indicated that the TINN model outperformed all comparative models tested about author identification and underperformed the other comparative models for the features extractions.

Variation in handwriting is a key feature to assess during forensic handwriting examination. Thomas et al. conducted a pilot study of genuine handwriting variations over a ten-year period [11]. The results imply that once an adult has acquired a particular handwriting pattern, the master pattern of each letter, as well as both class and individual characteristics, remain unchanged, however the size of the letters may change across age.

A study from China discusses that men and women differ in the neural basis of handwriting. Yang et al. used functional magnetic resonance imaging (fMRI) in a copying task to examine the neural basis of sex differences in handwriting in 53 healthy adults, highlighting the importance of considering sex as a factor in scientific research and clinical applications involving handwriting [12].

Gao and Wang conducted an exploratory analysis of dictated handwriting samples, including the definition of dictated samples, their relationship to experimental samples, practical problems, feasible collection methods, and some critical points that require special attention [13].

An article on the multidisciplinary research on signatures set out to determine the necessity of a comprehensive handwriting and technical study of documents for objective, comprehensive and complete research and to provide a sound and correct conclusion for the questions posed before the examination [14]. In 2020 this same group published an article on research of short simple signatures [15]. Also, on the topic of signature examination, Drobysheva et al. analyzed the theoretical aspects and conducted a literature review on the examination of signatures executed over a significant gap in time [16]. The authors proposed modern methodological approaches in their research of these signatures.

Cherpenko wrote of typical mistakes in forensic handwriting analysis of copies of handwritten entries [17]. The article gives examples of the most common mistakes in expert reports, including a review of both internal and external forms of peer review of ENFSI expert conclusions. To avoid most of mistakes described in the article the author proposes to follow relevant methodological references, to pay close attention to the quality of the examined object, and to adhere strictly to all intermediate stages of examination.

An historic review of the work and scientific creativity of forensic handwriting examiner, Professor Valeria Fedorovna Orlova (18.01.1926–18.03.2021), was published [18]. The author addresses Orlova's main theoretical works and methodologies and introduces the main tasks and capacities of forensic handwriting examination in Russia.

Kutskir wrote about the current forgery methods [19], and Sharma et al. considered disguised writing with the aid of specific individual writing characteristics: initial strokes, connecting strokes, and individual letter formation [20]. Another study [21] explored the similarities between complete and initial signatures of an individual for the purpose of author identification. While the team of Rani et al. [22] conducted a preliminary study on the authorship of disguised handwriting written with the unaccustomed hand.

In the study on the forensic evaluation of line quality features occurring in multi-generational photocopied handwriting Jasuja et al. attempted to study and evaluate the effect of reproduction process on several line quality features [23]. The authors tested five generations of photocopier reproductions by generating 4500 reproductions of 100 original samples of signatures from nine photocopiers of different make and model. Features such as the initial and terminal strokes of letters or characters, peculiar characteristics (e.g., gooping, striation marks) from the writing instrument, and those related with the writer, like the pen lifts, tremor, retouching, guideline, movement impulses were evaluated.

Another study involved the study of signature distortion in photocopying generations [24], specifically the effect of the photocopying process in five different subsequent generations on various features such as line quality, pen lifts and tremors, writing instrument characteristics (e.g., ink gooping), and features from the printer (e.g., line thickening). In this study, 2550 genuine signature samples were collected from different individuals, using different types of pens with different brands on various types of paper substrates commonly used for official purposes.

Welch conducted a survey of handedness in an attempt to provide information to the community about handedness in humans from various cultures and across historical timescales [25].

Ridolfi [26] described the results of an exercise for trainees to develop their own criteria for distinguishing among handwriting features, apply statistical methods to correlate features then develop a scheme to describe those characteristics that allows students to rate the degree of agreement between similar writings. By using a classification system involving letter shape, slant, height ratio, etc., trainees can then subdivide the group of writings by roughly half with each feature to arrive at the closest match to a given model.

Lister conducted research to show whether a novice could recognize the unique features of each person's handwriting in the known samples and locate those features in the unknown samples, whether natural or disguised handwriting [27]. Five handwriting samples were gathered from six individuals comprising one reference, three natural unknowns, and one disguised sample per person. A novice conducted analyses on every collected sample and conducted comparisons of the reference sample to the unknown and disguised samples to correctly source the unknown and disguised samples. The novice showed a high level of accuracy in correctly sourcing the natural sample but made erroneous conclusions when analyzing the disguised samples. This research demonstrate that some knowledge of the discipline can minimize misleading conclusions, which can be applied to forensic document examiners and compared to the analyses of non-examiners. The research also demonstrates that singular features are not enough to individualize a handwriting sample; multiple similar features are needed to form a definitive conclusion of a match.

A paper by Marquis et al. [28] explores how to account for the possibility of disguise when assessing a questions signature comparison. This work cases where there is a chance that the true writer has disguised the questioned signature. Options were proposed to logically take into account disguise in the assessment of the comparison of signatures.

Wang's article on the status of Chinese handwriting identification and the improvement of methodologies describes influences on handwriting and lays out the methodology of identification [29]. The methods of defining handwriting characteristics were explored, as were the number of characteristics and their degree of individualization. The author includes practical cases to support the theories proposed.

Miton and Morin, in their article on graphic complexity in writing systems [30] answer three central questions about the visual complexity of written characters and the evolution of writing: (1) What determines character complexity? (2) Can we find traces of evolutionary change in character complexity? (3) Is complexity distributed in a way that makes character recognition easier? Their proposed findings call for more detailed investigations.

A review of handwriting examinations of writings found on unusual surfaces was published by Tripathy et al. and encompasses the forensic investigations, their findings and success rate of such analysis including different writing instruments on handwriting over unconventional and unusual surfaces [31].

Pandey et al. [32] explored the hypothesis "higher the movement higher the skill" by conducting a comparative study of handwriting variation among weightlifters versus individuals who did not weight train. For the analysis the handwriting samples were taken from both groups and analyzed with result indicating a significant difference in the variation of the handwriting of the weightlifters versus non-lifters. The authors postulate that this was due to stiffness of muscles there is less movement in their body while writing.

#### 3.1.2. Handwriting education

There were numerous studies published about handwriting instruction which is an important topic for the forensic handwriting examiner to understand, especially in this globalized world where many countries no longer adhere to standard handwriting education. One study was designed to provide a comprehensive picture of the development and the longitudinal relations between spelling, handwriting speed, and handwriting quality at the word level [33]. Another study [34] aimed to determine further validation aspects of the Persian Handwriting Assessment Tool (PHAT) in primary school-aged children; results

indicated this tool was both valid and reliable.

A study by Watanabe et al. [35] aimed to clarify the developmental process of handwriting and to develop a new method for evaluating handwriting skills. They reported findings that the average pen pressure increased until seven years old, and then it was sustained at almost the same level as adults. They found similar relationships with spacing and size parameters, and handwriting skills overall, however the time required for handwriting execution increased until the age of seven, whereupon it decreased with age. In the development of handwriting skills, the study suggested that accuracy developed in an earlier stage and followed by the ability of speed control. Their method may also be useful in evaluating and supporting children with neurodevelopmental disorders, such as autism spectrum disorder, who are often affected by a lack of dexterity.

Semeraro et al. investigated the efficacy of teaching cursive writing in the first year of primary school [36]. Similarly, Rosario et al. wrote on the impact of three types of writing intervention on students' writing quality in fourth grade students [37]. A study from Mainland China [38] aimed to develop a tool to assess the handwriting ability of children aged five-six years old and to analyze its reliability and validity. Le et al. proposed modeling the relationship between motor skills and literacy on third-grade children through structural equation modeling; results indicated that in the third grade, the influence of fine motor skills on literacy is fully mediated by both executive functions and handwriting skills [39]. In Hong Kong, Tse et al. assessed early handwriting skill in kindergarten children using a Chinese name writing test [40].

There were several other articles concerning handwriting instruction in various parts of the world. One study set out to examine how writing was taught in grades one through three in Taiwan by surveying teachers [41]. Another surveyed the population of teachers in Brazil about their writing instructional practices, including the use of instructional practices supported by scientifically based research (evidence-based practices), perceptions of their preparation, and perceived self-efficacy in teaching writing [42]. In Chile, Banales et al. investigated teachers' perceptions about how they teach writing as well as their beliefs about preparation and efficacy to teach this skill [43]. This study focused on grades four-six in urban schools nationally in Chile. And in Norway, Graham, et al. conducted a national survey of writing instruction in primary grades with a view towards investigating how writing is taught, as well as the preparation and efficacy to do so [44]. Also in Norway, Skar, et al. studied handwriting fluency and the quality of primary students' writing in that country [45].

Handwriting instruction is a vibrant area of study in the pedagogical community and several other articles prove useful for the forensic community also. Graham et al. conducted a summary and review of various methods of writing education as well as concern, in the field [46], while Park et al. investigated haptic guidance methods for teaching children handwriting skills [47].

An important study contributing to handwriting examination of second languages was published by Salameh-Matar et al. This study focused on the transfer effect of handwriting performance from Hebrew as a second language to Arabic as the primary language. The sample consisted of 123 native Arabic speaking fourth grade students, of whom 64 attended monolingual schools, and 59 attended bilingual (Arabic–Hebrew) schools. The students' Arabic handwriting speed and legibility were evaluated as well as their handwriting automaticity, reading performance, motor control and non-verbal intelligence. Results showed that after controlling for reading speed, handwriting automaticity and motor control, the monolingual students outperformed their bilingual peers in handwriting speed but not in legibility [48]. A second study on this same general topic investigated the transferability of handwriting skills from Cyrillic to Latin-script alphabet. This study [49] was able to take advantage of a recent change of policy in Kazakhstan which gave an opportunity to measure this transfer and the influence of the number of years spent practicing Cyrillic on the quality of handwriting in the Latin alphabet.

The article by Feng et al. proposed to review the contribution of two writing modes – handwriting and keyboarding to writing performance. The findings emphasized the importance of handwriting on writing development despite the accessibility of keyboarding [50].

Kuznetsov et al. evaluated handwriting using laser speckle contrast imaging, a technique sensitive to both pressure and motion [51]. Laser speckle contrast imaging requires the use of only a simple laser diode and camera for image acquisition and is thus a cost-effective and practical tool for handwriting analysis, and in particular handwriting pressure and kinematics evaluation.

Bi et al. wrote that performing the correct pen-holding gesture plays an important role in handwriting efficiency and quality, especially for early education. In this paper, a detailed design and evaluation of the system is presented, which can identify the pen-holding gesture with a smartwatch when writing Chinese and Latin script and improve users' writing habits [52].

#### *3.1.3. Health, medicine, and/or neurological aspects of handwriting*

As a high-level motor skill, handwriting is often used as a predictor of various conditions, or a marker of progress of health conditions. Forensic handwriting examiners must understand that many conditions can have various effects on handwriting production and how this is accounted for during the forensic examination. The following articles discuss various conditions related to health, medicine and/or neurological aspects as they relate to handwriting.

The research [53] on signatures written by individuals with Alzheimer's disease suggested that the temporal, spatial and fluency characteristics of signature formation did not differ from signatures of healthy writers and that signature dynamics remained mostly stable over a one-year period. The authors also found that for stylized and mixed signatures, the dynamic signature feature variability and dementia severity are correlated.

Cognitive Impairments are cognitive deficits that are greater than expected for a person of a given age and level of education, but which do not significantly interfere with the daily life of the people affected. In the study presented by Cilia et al., a feature selection approach was used to determine the most effective features for predicting the symptoms related to cognitive impairments via handwriting analysis. The intention was to deepen the knowledge about the different cognitive functions affected by the onset of these diseases, as well as to improve the performance of the tools developed to support their diagnosis [54].

Talker et al. [55] assessed fine motor coordination in children with autism spectrum disorder (ASD). This developmental disorder is characterized by difficulty in communication, which includes a high incidence of speech production errors, which the authors hypothesized are partly due to underlying deficits in motor coordination and control, which are also manifested in degraded fine motor control of facial expressions and purposeful hand movements. In this pilot study, we computed correlations of acoustic, video, and handwriting time-series derived from five children with ASD and five children with neurotypical development during speech and handwriting tasks. The results highlighted differences in complexity of coordination across speech subsystems and during handwriting and helped discriminate between the two subject groups.

Another paper [56] presented a review of the literature of handwriting analysis for supporting the diagnosis of Alzheimer's (AD) and Parkinson's (PD) disease as well as of mild cognitive impairments, with the goal of updating the state-of-the-art research. The study also aimed at providing some guidelines on the features to use for representing handwriting as well as reviewed some widely used approaches for modeling handwriting. Cadola et al. published another literature review which divided the topic into three main sections: natural writing, aged or infirm writing with focus on AD, and available treatments and medications and their effects on handwriting production. This article had at its core the aim to provide FDE with casework involving writing of persons with AD [57].

Alfonso et al. also wrote about writing difficulties in patients with Alzheimer's disease (AD) and mild cognitive impairment (MCI) [58]. In their study, written latencies, inter-letter durations, mean word pen pressure and number of errors were measured. Results revealed that there was a significant difference between the control group and both groups of patients in written latencies and number of errors. However, in inter-letter interval or mean pen pressure there were significant differences only between the group with AD and the other groups. The relevance of these results for understanding the spelling impairment in AD and MCI are discussed.

A study to compare circle drawing performance in persons with Parkinson's disease (PD) that demonstrate impairment in repetitive finger movement and those that do not was undertaken by Stegemöller et al. Their results suggest that differing motor control mechanisms may play a role in the performance of fine motor tasks in persons with PD [59]. Another study promoted the use of handwriting exercise to improve fine motor function in PD [60]. Kaur et al. [61] produced a study specifically on the forensic examination of effects of PD on various handwriting characteristics. In this study handwriting and signature samples executed before and after the onset of Parkinsonism (both pre- and post-medication) were randomly collected from 70 participants. These handwritings were evaluated separately and compared inter-se for various handwriting characteristics with a qualitative and statistical approach.

A study by Crespo et al. aimed to explore the value of several measures of handwriting in the study of motor abnormalities in patients with schizophrenia spectrum disorders and bipolar disorder [62]. The handwriting of patients was characterized by a significant decrease in velocity and acceleration and an increase in the length, disfluency, and pressure with respect to controls. Results indicate that participants with a schizophrenia spectrum disorder or bipolar disorder exhibit significant motor impairments and that these impairments can be readily quantified using measures of handwriting movements. Further, they suggest that motor abnormalities are a core feature of several mental disorders, and they seem to be unrelated to the pharmacological treatment.

Ayaz et al. [63] examined whether or not there was a change in the handwriting of patients with bipolar disorder in periods of mania and remission. The results of this study determined severe changes in the handwriting of patients with bipolar disorder in a period of mania. Specifically, key results demonstrated the changes in handwriting in bipolar disorder, macrographia detected during the manic episode, and that handwriting features could be used as a screening tool for remission in bipolar disorder, as well as a prediction of a switch into mania.

Caligiuri et al. reported on handwriting movement abnormalities in symptomatic and premanifest Huntington's Disease (HD). In the study the authors [64] found that participants with HD exhibited significantly longer and more variable stroke durations, decreased handwriting smoothness, and increased and more variable pen pressures when compared with the healthy controls. Their findings support the clinical utility of dynamic measures of handwriting kinematics as a potential early behavioral biomarker in HD.

It is important for the FDE to recognize the effects of the movement disorder, essential tremor (ET). Research investigated the relationship between ET and anxiety and sleep disorder [65]. Another article [66] presented a novel approach for the early clinical diagnosis and monitoring of ET based on integrating handwriting and neuroimaging analysis.

Another disease that can affect handwriting of individuals significantly is rheumatoid arthritis (RA). Saini et al. reported [67] on qualitative and quantitative analysis of writings by afflicted persons prior to and once affected, as well as simulations of those writings. Their findings showed that almost all handwriting characteristics are significantly deteriorated by the disease, such as line quality and letter form, however slant, retouchings and overwritings are not affected. They further showed that the writing of a person affected by RA could be distinguished from the simulated writings by identifying non-genuine features, such as artificial tremor, hesitations, delicate retouching, unnatural pen lifts.

In 2019 Zabuha et al. wrote of the urgent need to study signatures made by the elderly handwriting undergoes significant changes in the process of transition from mature to advanced age, and over the past 50 years there has been a marked increase in the number of individuals of advanced age at a global level. One issue noted by the authors is that of experts conducting posthumous handwriting examinations of signatures without the benefit of contemporaneous specimen material. The authors conclude that a previously developed methodology for the forensic investigation of elderly writing remains effective and relevant, although further experimental research could improve this [68]. A related study by Vessio [69] provided an overview of the most relevant literature investigating the application of dynamic handwriting analysis in neurodegenerative disease assessment, while Impedovo et al., proposed a handwriting-based protocol that integrates handwriting/drawing tasks to provide a "cognitive model" for evaluating the relationship between cognitive functions and handwriting processes in healthy subjects as well as in cognitively impaired patients that can be used to detect and monitor neurodegenerative dementia [70].

A study of handwriting of the aged comprised the examination of short handwritten records executed by elderly and senile persons [71]. The article attempts to substantiate and systematize theoretical knowledge on the study of short handwritten records executed by elderly and senile people through an assessment of the literature and forensic practice. The authors considered the physiological mechanisms of the formation of writing skills and how the features change due to various conditions during the ageing process, including motor coordination disorders, conditions of the musculoskeletal system, nervous system, circulatory disorders that can affect the stability of handwriting features. Testaments, contracts of sale and donation, bank documents are often signed by people of elderly and senile age shortly before death resulting from a serious long illness. Features of writing motor skill functioning in the elderly can lead to a slowdown in the tempo of movement, decrease in their amplitude and speed, and in the plasticity of movements.

An interesting article reported on the case of a right-handed Caucasian woman who developed mirror writing following a non-aneurysmal, non-traumatic subarachnoid hemorrhage. Given the rarity of natural mirror-writing this sort of case study is of particular interest to the FDE community [72].

#### *3.1.4. Interpretation of handwriting findings*

An article by Marquis et al. detailed the forensic investigative and evaluative assessment of handwritten X-marks [73]. An experimental study was designed and X-marks from 75 right-handed and 25 left-handed writers were collected and classified according to their stroke sequence. The results of this empirical study were first used to assess handedness of the writer, together with a development on the risk of misleading evidence as a measure of the method performance. The results were then used to assess writership of a given person rather than an unknown person. This paper shows that following the ENFSI recommendations for evidence interpretation may require only a small dataset collected for the case needs. The procedure of evidence interpretation detailed in this paper may be followed by any examiner interested in applying a Bayesian approach on simple data collected for assessing the results of a given case, should this concern an X-mark or any other handwritten sign or letter.

Vastrick et al. published their study on measuring the frequency occurrence of their expanded list of handwritten numeral characteristics [74]. The premise of this current and future follow-up studies is to expand on the initial lists of information incrementally by expanding the number of features and the number of writers. A total of 34 numeral features was selected by the authors as candidates for this study and tested through an attribute agreement analysis. Based on the results of the testing, 17 new features have been added to the list of proportions.

#### 3.1.5. Conference presentations and workshops

In the period under review there have been numerous presentations given to various forensic conferences on the topics covered in this section. These presentations are not described here; however references have been provided. With respect to handwriting and signature examinations, 32 presentations were given [75–106], while three presentations specifically covered the examination of numerals [107–109], and one spoke to X-marks [110]. There were ten presentations concerning the factors that influence handwriting [111–120]. Two presentations covered the topic of non-Latin handwriting scripts [121,122], and two others covered the collection of handwriting exemplars [123, 124]. One workshop was presented during this period that dealt with the examination of handwriting - specifically signatures [125].

### 3.2. Digitally captured signatures/handwriting

This relatively new topic to this literature review comprised 28 articles, 6 workshops, and 30 conference presentations. Given the move towards digitally captured signatures (DCS) for many applications, forensic handwriting examiners are spending considerable time in researching and sharing best practices for their analysis.

In 2019, Caligiuri and Mohammed [126] analyzed dynamic features of digitally captured signatures to test the hypothesis that Alzheimer's disease (AD) signature features will show greater variability compared with signatures from age-comparable healthy subjects. The authors collected 335 signatures from individuals with dementia of the AD type, and 358 from the control group using a non-inking pen with a digitizing tablet. Overall, the results suggest that signature writing is preserved in AD.

Li et al. [127] aimed to formulate a method to automatically evaluate the tilt and slope of students' Chinese handwriting using digital handwriting tablets. The relationship between the tilt and slope features of the students' Chinese handwriting, as well as other demographic and handwriting features was analyzed, and the results demonstrated a relationship that can be adopted as an indicator of special education needs diagnosis.

Diaz et al. [128] proposed a novel set of anthropomorphic features for signature verification. These features are generated using the pen-tip position and orientation when signing on a digital tablet, and characterizes the movement through simulation of the shoulder, the elbow and the wrist when signing.

Angelillo et al. [129] propose a novel technique for the automatic detection of dementia based on tests developed on a digitizing tablet, equipped with an electronic pen. The test measures reflect the dynamics of the handwriting process, particularly the in-air trajectory pauses and hesitations while the pen is not in contact with the pad surface. Handwriting measures can then serve as an input to machine learning algorithms to automatize disease detection.

The aim of Dziechciaruk's article [130] was to analyse the interaction between the curvature and the speed of execution of handwriting: straight lines or gentle large arcs are executed at a higher speed than short, more curved arcs. The correlation between the speed of writing and the curvature of the handwriting can be mathematically expressed by applying the isochrony principle. The paper also demonstrates how this correlation can help to evaluate the quality of a graphic line.

In 2019, to solve the problem of developing a methodology for the study of signatures made using a tablet with a stylus pen, a commission was formed from the experts of the Center for Forensic Expertise of the Ministry of Justice of the Republic of Kazakhstan in the field of forensic handwriting and computer technology expertise [131]. Ismailov's article reports on the work to learn from the experiences of foreign forensic document examiners that work with electronic documents and develop a methodology for Kazakhstan.

In the Electronic Confirmation of Receipt (Elektroniczne Potwierdzenie Odbioru – EPO) program implemented by the Polish Ministry of Justice since 2014, the addressee signs a confirmation of delivery with a digitally captured signature [132]. The aim of the study by Dziedzic and Ferenc was to evaluate the suitability of biometric data of signatures captured in the EPO system for forensic handwriting examination by analysing the type of recorded numerical data and verifying the possibility of calculating the most important parameters of signatures on their basis.

A fundamental article by Geistova et al. presents recommendations drawn up by forensic handwriting examiners (FHE) associated with ENFHEX (ENFSI) in a project aimed at defining best practices in forensic examination of digitally captured signatures [133]. The aim of this technical note, written by FHEs, is to provide hardware and software developers, suppliers, and user institutions of digitally captured signature technologies with guidelines regarding the optimal information that FHEs require for forensic handwriting examination.

Fuglsby et al. [134], conducted an experiment to deploy an automated feature extraction program to generate feature dissimilarity scores and population distribution functions for ranking these feature dissimilarity scores among pairs of handwritten phrases across different phrases and styles of handwriting. A second experiment was to utilize these dissimilarity scores and distribution functions to design a series of difficult case scenarios for FDEs to evaluate. This study demonstrated that feature dissimilarity scores acquired using automated processes and their distributions are closely aligned with FDE decision-making processes supporting the heuristic value of the two-stage evaluative framework.

Tolosana et al. hypothesized that traditional authentication systems are enhanced by the incorporation of dynamic handwritten biometric information [135]. This study evaluates the advantages and potential of incorporating biometrics to password-based mobile authentication systems, asking the users to draw using their finger each digit of a password on a device touchscreen instead of inputting the digits by typing.

An article by Hu et al. [136] proposed a novel model (SSDCNN) which uses the stroke sequence information and eight-directional features of Chinese characters for online handwritten Chinese character recognition (OLHCC). SSDCNN learns the representation of OLHCCs by incorporating the natural sequence information of the strokes, incorporating the eight directional features. The model was experimentally evaluated, and the results reported as accuracies of 97.86% for SSDCNN and 97.94% for its adaptive version.

Heckeroth et al. [137] compared digitally captured signatures and conventional signatures. Statistically significant feature differences between these two kinds of signatures were noticed. However, for the examiners, these factors do not restrict the comparability between these two kinds of signatures but with caution.

Linden et al. [138] performed a signature acquisition process, where selected signatures served as reference and control material in a hypothetical scenario involving disputed signatures. Other signatures from the acquisition process were used as background data to inform prior distributions about model parameters. Different levels of accuracy were observed with reference to different models, background data, feature selection and reference signatures. While the results were encouraging, suggesting that selected features collected from dynamic signatures could be discriminative, this study highlights the limitations of current approaches to infer authorship in the presence of dynamic signatures and suggests that a new set of data should be collected for each case.

Zimmer et al. [139] compared digitally captured signatures captured with 26 different combinations of hardware and software. They found that significant variations in scaling and coding of data occurred when different hardware and software combinations are used. Normalization of the signature size was recommended, however, even when signature data was normalized, the data captured with various solutions could still exhibit differences.

Guerra-Segura et al. [140] studied signature verification with a view towards improving capture, processing, and classification of signatures. This article provided good background information on signature verification and proposed a novel and robust contactless, in-air signature

verification system using a commercial system chosen for its stability and good performance with this task. Based on a study of 100 writers who created ten genuine and ten forgeries each, the authors tested a commercial device to characterize in-air strokes and achieved very good signature verification results in comparison with other technologies.

Another article about online signature verification addressed the challenges of this task in the pattern recognition field [141]. The main challenge to overcome for this task was the variability of handwriting both within an individual (intra-class variability) and as compared to other individuals (inter-class variability). The five-model system proposed by the authors reached a classification accuracy of 100% when applied to genuine signatures of public datasets, and above 99% accuracy when trained on one dataset and applied to others.

Begum et al. [142] also proposed a model for user authentication using digital pen-tablet sensor data. Their research proposed a robust and efficient user identification system using an optimal feature selection technique based on features from the sensor's signal of pen and tablet devices. The experimental results achieved sufficiently accurate outcomes for user identification with low computational cost.

Younas et al. [143] worked with the Apple pencil, a digital sensor pen, and an iPad as the digital sensor screen to capture a new online handwriting dataset. The aim was to develop a feature set that can classify online written sequences into text, mathematical expression, and plots or graphs for further research purposes.

Lunardini et al. [144] developed a smart pen with force and motion sensors, from a traditional inking pen, that could be used to assess natural handwriting. This development aimed to test the smartpen and its sensors, combined with algorithms, and to use this technology to detect age-related changes in handwriting, such as tremor. The authors reported good validation of the technology, and findings for the age-related analysis were promising. The test involved 43 healthy older and younger adults; it was observed that the handwriting from the older adults was characterized by an increase of temporal writing measures, a more uniform writing pressure, and more repetitive and predictable tremor oscillation components. According to the authors, this smart pen combines the advantages of the digitizing tablet technology with the naturalness and ease of use of traditional pen-and-paper.

Sharma et al. [145] conducted a comparative analysis of digitally captured signatures with pen-paper signatures. The aim of this study was to identify any differences between two sets of signatures written by the same individual on a digital writing pad with the help of a stylus and on paper with a conventional writing instrument. The similarities and differences with respect to class and line quality features between both signatures were analysed. It was observed that despite differences between the signatures produced by the same author, it is still possible to establish the authorship of the digitally captured signatures.

Nolazco-Flores et al. [146] researched computerized decision support systems for PD dysgraphia diagnosis. The authors added spectral and cepstral features to the already-used temporal, kinematic, and statistics features, and with their proposed model lower computational complexities improved classification accuracy to 98.57%, and outperformed conventional state-of-the-art models for all tasks.

Faundez-Zanuy et al. [147] presented a pressure characterization and normalization procedure for the online acquisition of handwriting. Their goal was to analyze the real scenarios where users enroll their signatures with one stylus and later produce test samples using a different stylus model with different pressure response. The testing confirmed that stylus pressure responses are not linear, and that the different stylus tested possessed different responses. As pressure is a useful feature of writing identification, this parameter cannot be discarded and so the normalization is an important factor for signature verification.

In fact, in digitally captured signature (DCS) solutions, force is captured and presented as pressure levels, however the relationship between exercised force and assigned pressure levels is not provided by manufacturers of the technologies [148]. This research team constructed experiments to show the correlation of this force-pressure relationship using a combination of three different digitizers, six different styli, and four different capturing software. Through calibration and the use of the Zeta function they developed a method for the normalization of force on DCS data.

In this study, Linden et al. [149] tested a probabilistic model based on the calculation of Bayes' factors to evaluate dynamic signature evidence in the form of multivariate data. Data sparsity, feature combination and feature discriminative power were investigated. The results showed an accuracy rate above 90% even when a limited number (5) of reference signatures was available, and that 15 signatures was sufficient to obtain accurate and reproducible results. The results also show that the global features characterizing dynamic signature are correlated, so a multivariate approach is recommended, and that the features selection should be case-specific.

Several articles were published in 2019 however were available online just prior to this review's start and are therefore included in the references because of their relevance, however they are not detailed in the text [150–153].

This topic of DCS was widely popular for conference presentations and workshops during the review period, with 30 presentations [154–183] and six workshops [184–189] conducted. These presentations, ranging in subject from dynamic data and in-air trajectories to DCS hardware and software and sample collection are not described here, however references have been provided.

### 3.3. Automated systems

In the classic field of forensic document examination, the use and even knowledge of automated systems for handwriting and signature analysis has been minimal. However, some laboratories have worked in this space for decades already and have worked to bring the expertise from those academics and industries that study automated systems to an operational point in forensic science. It is with this purpose that this section is included in this literature review.

While the research into various aspects of automated systems for various tasks related to handwriting and signature analysis is significant, one relevant textbook [190] and104 articles [191–294] are included in the reference section, along with 35 conference presentations, including a workshop [295–329]. These references were sourced from various journals to inform the FDE reader and manager of the state of this science with respect to the forensic examination of handwriting. Due to the large number of references not all are described here.

A key text that emerged during the review period was that of Fischer et al.: Handwritten Historical Document Analysis, Recognition, and Retrieval – State-of-the-Art and Future Trends [190]. This book discusses the entire processing chain of layout analysis, handwriting recognition and retrieval of historical manuscripts including related research projects and future trends. As a text this work provides foundational background of use for the forensic community with respect to automated systems.

Faundez-Zanuy et al. [191] present a review of handwriting analysis and signature biometrics in e-Security and e-Health applications, noting that from a human behavior perspective, online handwriting biometrics may be more appealing and informative than other modalities. The authors conclude that security and health applications of handwriting analysis can no longer be considered as separate fields, and that a combination of identification and health properties of biometric handwriting information is a goal.

Dhieb et al. [192] presented a biometric based recognition system for forensic document examination capable of identifying a document's author. The aim of this research was to develop an online text independent multilingual writer identification system based on new features able to efficiently characterize the biometric, the kinematic and the graphic data. The authors proposed a new model to extract static and dynamic features from online handwriting after preprocessing and

stroke segmentation, followed by the use of Deep Neural Network as a classifier. This proposed system outperformed existing writer identification systems on Latin and Arabic scripts and promises to be useful for forensic handwriting examination.

Ishihara S [193]. used a score-based approach with a bag-of-words model to estimate likelihood ratios. The score of the documents under comparison was measured using different distance measures. The best results are obtained with Cosine distance with any number of the most-frequent words for all document lengths. The lengths of documents tested were 700, 1400 and 2100 words.

Ishihara and Carne [194] continued this research by comparing the score-based (univariate) method to three features-based (multivariate) methods built on Poisson models for estimating the LRs of textual evidence. The log-likelihood ratio costs indicated that the features-based methods outperform the score-based method, and a selection of features can improve the performance for the feature-based methods.

Enhanced writer identification algorithms were used by Shaus et al. combined with forensic document examination to examine the handwriting from ostraca (ink inscriptions on potsherds) dated to ca. 600 BCE [195]. The aim of this study was to predict the literacy level of a region of the biblical kingdom of Judah. In this study, handwriting analysis of 18 inscriptions, including more than 150 pair-wise assessments of writer's identity was conducted. The examination was performed by two new algorithmic handwriting analysis methods and independently by a professional forensic document examiner. This study demonstrated substantial agreement between the results of these independent methods of investigation, while demonstrating widespread literacy in the late 7th century BCE Judahite military and administration apparatuses.

This study by Popovic et al. [196] takes an innovative approach in palaeography to determining how many writers can be identified when the writing style is near uniform. In this study of the Great Isaiah Scroll (1QIsaa), pattern recognition and artificial intelligence techniques were used to innovate the palaeography of the scrolls, providing new, tangible evidence that ancient biblical texts were not copied by a single scribe only but that multiple scribes would collaborate on the production of one particular manuscript.

Juola [197] used a computer program to compare a known document and a questioned document to determine if the same author wrote them. The documents are analyzed in five different ways (words used, word lengths, character n-grams, most common words, punctuation) and the combination of the results is used to produce a final answer. The program was tested on a large database, and the measured accuracy was 77%.

Automated writer verification/identification on a particular set of handwritten patterns, like the speed of an individual's writing is a challenging task, especially when the system is trained using a different set of writing patterns (e.g., normal speed) of that same person. Adak et al. [198], experimentally analyzed if there exists any implicit characteristic of individuality which is insensitive to high intra-variable handwriting. They studied writer identification/verification from highly intra-variable offline Bengali writing. The team generated two handwritten databases from two different sets of 100 writers and enlarged the dataset by a data-augmentation technique for their testing. The authors found that while their automated system improved with pre-training, their method did not perform well for the initial goal.

Fuglsby et al. [199] studied the relationship between two systems: FLASH ID®, an automated handwriting/black box system that uses measurements extracted from a static image of handwriting, and MovAlyzeR®, a system that captures kinematic features from pen strokes. For their study the authors collected 60 phrases from each of 33 writers in both cursive writing and hand printing, resulting in thousands of sample pairs for examination. The writing features from these pair samples were processed using both systems and the output scores analyzed. The observed results indicate that dissimilarity scores based on kinematic spatial-geometric pen stroke features (e.g., amplitude and slant) have a statistically significant relationship with dissimilarity scores obtained using static, graph-based features used by the FLASH ID® system. These results suggest that studies of biometric discrimination using an open handwriting kinematic feature analysis system supports the validity of biometric matching algorithms based on a black box algorithm.

Automated analysis methods for signature authentication were also studied by the team of Kurowski et al. [200]. The developed system analyzed dynamic features obtained from a biometric pen's sensors, as well as static features (i.e., the shape of the signature); by adding the dynamic data, such as pen tilt, pressure, and speed, to the overall shape of the signature, they found significant improvement to the authentication system results.

Leveraging machine learning in forensic sciences has been hindered by its almost unfalsifiable nature [201]. Marcinowski worked to develop a top interpretable neural network for the identification of writers of handwritten documents that would satisfy forensic and scientific standards and have good accuracy.

Crawford et al. [202] focused on the problem of comparing a person's handwriting to a document of unknown provenance using the shape of the writing, as is done in forensic applications. They proposed a method for processing scanned handwritten documents to decompose the writing into small graphical structures, often corresponding to letters, then introduced a measure of distance between two such structures. These measurements were the basis for an algorithm to cluster the graphs based on structural attributes, creating a template for sorting new documents. A Bayesian hierarchical model was used to capture the propensity of a writer for producing graphs that are assigned to certain clusters, thereby providing an evaluation of identity.

Given the field of automation and machine learning has several conferences dedicated to various aspects of handwriting analysis, there were many presentations given over the period of this review that required assessment for inclusion in this article. Of these select ones are included in the reference section [295–329], however are not described here.

### 3.4. Indentation development

Indentation development of latent writings and marking is a classic method used in forensic document examination. Three articles, ten conference presentations, and one workshop were dedicated to the techniques used to develop and interpret latent indentations.

Sadiq et al. [330] tested the use of erasable marker pen ink as an alternative application of toner to develop indentations after the charging process with ESDA. Results showed that it was possible to substitute toner by erasable marker pen ink, however the revelation was a success for seven of the 11 documents (10/11 with toner) and the quality was considerably lower.

Welch conducted a small study [331] specifically to investigate the phenomenon of imaging handwritten indentations made through a plastic document wallet. This preliminary study resulted in findings consistent with previous work, however raised questions for further research into the effects of plastic films of various composition on the electrostatic detection of indented and embossed handwriting.

Green [332] investigated the transfer of rubber stamp images onto documents wherein rubber stamp impressions were revealed upon latent indentation processing. Of note in this study is that the stamps were sourced to the shipping circumstance of the documents and were able to be deciphered due to the chemical composition of the inks and not the typical paper fiber disturbances associated with pen pressure strokes in handwriting indentation determinations.

As with the previous sections, the conference presentations [333–342] and workshop [343] on this topic are not described herein but are included in the reference section.

## 4. Forensic document examination

This section on Forensic Document Examination comprises all other areas typically associated with the field that do not include handwriting examination. This section is very broad, including subjects such as the analysis of the document components, substrates, methods of production, and dates of production, and has been organized into various subsections for ease of comprehension, albeit sometimes subjective.

### *4.1. Equipment Advances and Updates*

As with many of the forensic sciences, the resolution of FDE problems using analytical technique relies upon horizontal scans of other fields of scientific study, and borrowing methods and techniques developed elsewhere for application to FDE. This is particularly true in the field of FDE, which is not in and of itself a classical field of academic study. Practitioners in those forensic document laboratories with capacity to conduct analytical examinations rely upon advances in the pure and applied sciences, as well as in areas such as art conservation to adapt methods and instrumental techniques to the problems facing document examination, such as document dating determinations.

It is not possible to consider the many and various equipment that are or have been used in the forensic analysis of documents. Some techniques such as Thin Layer Chromatography have been in use since the beginnings of component analysis, while others are improved-upon methods or technologies applied in new ways. It must be noted that non-destructive techniques are always preferred to any sampling for analysis, as any damage to the document should be kept at a minimum as much as possible.

Twenty-six articles are included in this section to show the use in forensic document examination of analytical techniques. A selection of these is described below, however the majority are included in reference only [344–370] as they mainly deal with the analysis of historic documents and their components, although these documents are also examined by the FDE. A further 16 presentations [371–385] were given at conferences and pertain directly to FDE, as well as the two workshops [386,387] concerning novel analytical techniques in the field.

Tournie et al. [344] successfully applied shortwave-infrared (SWIR; 1000–2500 nm) hyperspectral imaging (HSI) to an unrolled papyri revealing portions of Greek text hidden on the back from 220 years ago. The application of SWIR HSI produced better contrast and legibility, including on the extensive text preserved on the front compared to former imaging of other papyri at 950 nm. These results confirm the importance of applying advanced techniques to ancient papyri, as well as to other documents of similar condition.

Khan et al. [345] recognized the important of multispectral examination to forensic document examination and therefore set out to construct a low-cost scanner designed to capture multispectral images of documents. A standard sheet-feed scanner was modified by disconnecting its internal light source and connecting an external multispectral light source comprising narrow band light emitting diodes (LED). They tested the device by scanning documents while illuminating the scanner light guide with different LEDs, capturing one spatial dimension x, while the (y, l) dimensions were sequentially acquired by feeding the document and tuning the illumination spectrum. The authors created this portable system with less than one hundred dollars and expect it to be used for applications in verification of questioned documents.

Through hyperspectral imaging and data analyses, pigment inks can be identified, and their printing/writing characteristics judged, thereby assisting in authenticity assessments [346]. However, due to the lack of databases with appropriate reference information, rapid and accurate identification is difficult in practice.

In this paper, to simulate the expert identification process, the researchers explored the idea of combining hyperspectral imaging and Atlas intelligent learning. The actual test results show that the convolution neural network based on the atlas features provided good results, and that adding multivariate spectral features can improve the accuracy significantly.

One article [347] investigated the inks, pigments, and papers of four Moroccan illuminated manuscripts from the 18th century. The authors employed X-ray diffraction (XRD), energy-dispersive X-ray fluorescence spectrometry (EDXRF), scanning electron microscopy coupled to energy dispersive X-ray spectroscopy (SEM–EDS), Raman and attenuated total reflection Fourier transformed infrared spectroscopy (FTIR-ATR) in various combinations to characterize the various components in these documents. SEM also allowed for the examination of the typical morphology of the paper highlighting effects of the degradation process.

Pereira et al. [348] explored the use of synchrotron-based scanning macro-X-ray fluorescence (MA-XRF) technique in the analysis of artwork bearing erasures including of the signature to determine authenticity. Using the resultant elemental maps, the signature could be reconstructed. Further, the elemental maps allowed the authors to determine the pigment composition was determined. The painting was also investigated by SEM-EDS, and FTIR techniques. Those results, in addition to the supporting elemental maps, allowed additional information to be obtained.

Microscopy can detect the presence of coating on paper, but not characterize it [349]. The team of Li et al. researched methods to characterize coatings on ancient papers from China, combining microscopic observations, surface elemental analysis, micro-CT imaging, and RAMAN spectroscopy. The documents were analyzed stereoscopically using high-quality Differential Interference Contrast (DIC) imaging, followed by the analytical techniques. The team applied micro-computed tomography (micro-CT), hand-held X-ray fluorescence (hhXRF) and Raman spectroscopy for non-destructive characterization of coating and coating pigments on these ancient papers.

The following list shows other possible analytical techniques aside from the routinely used stereomicroscopy, indentation developers, and specialized lighting (excitation/emission) techniques:

- Accelerator mass spectroscopy (AMS)
- Attenuated total reflectance - Fourier Transformed InfraRed spectroscopy (ATR-FTIR)
- Field emission scanning electron microscopy/energy dispersive X-ray spectrometry (FE-SEM/EDX)
- Fourier Transformed InfraRed spectroscopy (FTIR)
- Gas Chromatography - Flame ionization detector (GC-FID)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Pyrolysis- Gas Chromatography - Mass Spectrometry (Py-GC/MS)
- Thermal desorption - Gas Chromatography/Mass Spectrometry (TD-GC-MS)
- High-performance liquid chromatography (HPLC)
- Hyperspectral imaging (HSI)
- Hyperspectral imaging in the near infrared range (HSI-NIR)
- Laser-induced breakdown spectroscopy (LIBS)
- Microspectrophotometry
- Optical coherence tomography (OCT)
- Particle-induced X-ray emission (PIXE).
- PhotoAcoustic imaging
- RAMAN spectroscopy
- Rutherford backscattering spectrometry (RBS)
- Scanning electron microscopy (SEM)
- Scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDX)
- UV–Vis spectrophotometry
- X-Ray Diffraction (XRD)
- X-ray fluorescence (XRF)

### *4.2. Writing Instruments and Inks*

This section includes articles and other work in the study of writing

instruments, including their inks, as well as inks for printing devices. Characterization or comparison of these elements of a document may be useful in determining links between documents or devices used in their production, and so is a common challenge in FDE. The characterization of inks is also important in the assessment of how best to determine dates of introduction or production of documents based on these inks.

In the period under evaluation in this review there were 33 articles [388–400], [401–420] and 20 conference presentations [421–440] that can be assigned to this section.

In this study [388] of thin layer chromatography (TLC), Aginsky tested four different solvent systems for analysis of five blue and black pen inks (water-based and oil-based inks). The author observed that the best result was obtained with the solvent systems composed of ethyl acetate, isopropanol, water, and acetic acid, and that it was more efficient than the solvent system (ethyl acetate, ethanol, and water) recommended in the current SWGDOC Standard for Test Methods for Forensic Writing Ink Comparison.

Copper et al. [389] analyzed ballpoint pen inks directly from paper using a new direct sampling technique for capillary electrophoresis (CE). The team tested blue, black, and red Bic ballpoint pen inks, extracting, and injecting the dyes directly from the paper into the CE instrument without any sample pre-treatment. Their study showed that this is a viable technique for the analysis of writing inks, reducing analysis time, generating high concentrated sample, and is minimally destructive.

Gorziza et al. [390] evaluated a commercial application for mobile devices, PhotoMetrix PRO®, for the differentiation of blue ballpoint pen inks. This app is a qualitative and colorimetric analysis tool that applies uni- and multivariate analysis, including Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Partial Least Squares Discriminant Analysis (PLS-DA) from digital images data. The results of this non-destructive and easy-to-use method showed good differentiation between the most common blue ballpoint pen inks in Brazil. This method can be used to confirm subjective results, proving useful when more sophisticated instruments are not available.

Gautam et al. [391] analyzed fifty black ink samples (25 ball-point and 25 gel-point pens) with Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy conjoined with chemometric method of Principal Component Analysis (PCA) and PLS-Discriminant Analysis (PLS-DA). The aim of this study was to characterize black ink samples by devising a simple, non-destructive method that would also ascertain the source of black ink used in the alteration and obliteration of fraudulent documents. This work also helps to maintain a library on spectroscopy results of these 50 black ink samples.

Nehring et al. [392] offer a non-destructive method to characterize the composition and manufacturing process of ancient iron-gall ink. Using 2D scanning micro-X-ray fluorescence in combination with infrared reflectography allowed for the identification of elemental iron and copper components, microscopy under UV light indicated the presence of tannins.

Hilario et al. [393] used Laser Induced Breakdown Spectroscopy (LIBS) for the rapid and semi non-destructive elemental analysis of ball-point pen writings performed directly from paper surfaces. The aim of this proof-of-concept research was to obtain maximum differentiation between seventeen different pens with a minimum number of pulses. The instrumental variables, the delay time, laser pulse energy and number of pulses per point, were evaluated. The copper (Cu) atomic emission line demonstrated the best discrimination for two pens of the same color; however, the background contribution of cheque paper limited the multi-element profile of the technique. The results obtained by LIBS analysis were verified by microwave-assisted digestion of inks and analysis by ICP OES. Lastly, a real situation test was conducted where a forged document was analyzed by the proposed methodology as an alternative to distinguish between two inks of the same color, originating from different pens.

Chen et al. [394] analyzed pencil marks and leads by LIBS to identify the kind of pencil. Four pencils with different hardness and blackness were tested. Spectra of pencil leads were treated by BP neural network and by K-nearest neighbor (KNN) combined with a PCA. The identification accuracies were 97.9% for BP neural network and 98.33% for PCA-KNN.

Asicioglu et al. [395] prepared disappearing inks to analyze the effects of thymolphthalein concentration and pH of the ink solution on the disappearance time and on decipherment. The authors used both a video spectral comparator (254 nm illumination) and a chemical method (NH3 vapor) to decipher the disappeared text. It was noted that one of the prepared inks could not be deciphered using either method, and that the overall results were not different for these two methods. By using NaOH spraying method, ink reappeared but the substrate and ink could be altered by these chemical methods. Hilal and Twfiq also studied disappearing inks [396] because of their potential for abuse for forgery and counterfeiting. The researchers prepared disappearing inks using different concentrations of thymolphthalein (Th-ph) and O-Cresolphthalein (O-Cph), then applied them to different types of handwriting papers. By deciphering the faded documents using different methods, it was found that the ink stability was better when the alkali concentration was increased. Commercial paper surfaces offered more handwriting stability than other papers. All the faded documents were visible when treated with alkaline solution, however there was no effect when exposed to heat.

Liu and Li [397] distinguished six black and six blue erasable gel pens by brands using spectral analysis (IR and fluorescence light sources), FTIR and microspectrophotometry. The authors recommend conducting further tests to validate this method. Zhao et al. [398] analyzed 30 erasable pens of different brands, models and ink colors by FTIR. They classified them using chemometrics methods (PCA and heatmap). Chayal et al. also studied erasable inks [399]. Their literature and survey revealed that some erasable ink pens were consistently used to commit economic frauds in bank instruments like cheques, withdrawal slips, demand drafts, fix deposit receipts, counterfeit currency, and other essential documents. The aim of their study was to develop simple, rapid, sensitive, eco-friendly procedure to retrieve original writings of erasable ink.

Blue, black, and red inks of different types (gel ink, ballpoint, and liquid ink) from different manufactures.

[400] were analyzed by Hyperspectral imaging (HSI). The spectra were pretreated then a t-SNE (t-Distributed Stochastic Neighbor embedding) algorithm was applied to reduce the dimensionality of the data. The t-SNE visualization in 2D was compared with the Principal Components Analysis (PCA) visualization. According to the results obtained by the authors, the t-SNE outperformed PCA for dimensionality reduction: better visualization and improvement in clustering quality.

Naeim Mohamad Asri et al. [401] proposed a method for the discrimination of red gel ink pens using an alternative to traditional chemometrics techniques. This team used unsupervised self- organizing feature maps and partial least squares discriminant analysis to classify red gel inks using a dataset acquired from Raman spectroscopy, then identify these inks by comparisons to inks in a spectral library. Their method was able to correctly classify and identify the source of the red ink in blind testing.

Eleven fountain pen inks (three blue, four black and four green) from Pakistan were analyzed by GC/MS to discriminate them [402]. For each color, the discriminating power was one (1).

Moore and Buzzini [403] provided a review of porous tipped writing instruments to thoroughly discuss the developments of the porous-tipped pen throughout history, the criteria that help differentiate stroke features between porous-tipped pens and other fluid pen inks, and any information gathered about their properties. The authors collated the results of their survey which included specifications from 141 different brands and 966 individual products from 2018 to 2019. The review comprised existing porous-tipped pen studies and the findings of the present open-source survey allowed to highlight several challenges that the forensic document examiner must face when asked to

characterize and compare graphical, physical, and chemical features left by porous-tipped pens on a questioned specimen.

Buzzini et al. [404] evaluated whether Raman data from the three colored dots (cyan, magenta, yellow) of an inkjet-printed document constitute, all together, a chemical signature sufficiently discriminating to provide reliable investigative leads in a time-effective and non-destructive manner. Three variants of linear discriminant analysis [PCA-LDA; PLSDA; sparse LDA] were evaluated on 231 Raman spectra of a set of 11 inkjet printer ink samples, which were previously compared visually. Results showed that although spectral visual comparisons are still superior to differentiate Raman spectra on the basis of minor peaks, sparse LDA provided the highest classification potential (i.e., highest accuracy) for individual colors, and that the three methods performed equivalently when the spectral data from the three colors were combined.

In their study, Lian et al. established a simple and widely applicable GC–MS method to identify different components in inkjet printing ink on printed documents [405]. A universal GC–MS method was developed to analyze various ink components extracted from inkjet printouts. The results indicated that several components detected and identified across 195 inks could be used to distinguish printer manufacturers. A trend of decreasing solvent concentration over time was observed through the continuous monitoring of seven samples. The results show that this method is useful for forensic classification purposes, and can be useful regardless effects of storage environment, paper, or printer. The application of this method in the analysis of counterfeit banknotes illustrated its feasibility and applicability.

Kissel et al. [406] worked to develop a robust methodology and data analysis procedure to identify red dyes in artwork where dye collection is inaccessible by traditional methods. With Surface-Enhanced Raman Spectroscopy (SERS) it was possible to obtain identifying molecular information from dilute and degraded dyes. The team used a minimally invasive, soft-mechanical sampling method to gently contact printed paper using a customized polymeric hydrogel surface with an exposure area of about one $mm^2$ to collect micrometer-diameter colorant particles. To validate that the sample collection methodology is minimally invasive, test papers were photographed before and after sampling under UV and white light; and DART-MS analysis of the sampled area was conducted. A reference library of SERS spectra was built and used by a spectral-matching genetic algorithm (GA). Fifty individual GA runs returned results that precisely matched at least one dye component in 48–50 of the 50 runs and matched both dyes in a mixture between 29 and 50 of the 50 runs.

Aitken et al. [407] interpreted results of microspectrophotometry (MSP) spectra for ink by using likelihood ratio determined by functional data analysis. Ink lines from 40 inks were drawn on white printing paper, then fragments cut and fixed to a microscope slide then placed on the microscope stage of the MSP instrument. The approach contrasted with the CIE approach for ink discrimination and the performance was found to be comparable.

Yadav and Sharma [408] classified fiber tip pens using attenuated total reflectance (ATR) – Fourier transform infrared (FTIR) spectroscopy in tandem with chemometrics. The authors chose this study because of the popularity of these pens as writing instruments and because little analytical work has been done on the fiber-tip pen inks. In this study, the authors attempted to classify fiber-tip pens of black, red, green, and black color of different brands into their respective brands using Attenuated total reflectance (ATR) – Fourier transform infrared (FTIR) spectroscopy supplemented with Principal component analysis (PCA), and Linear discriminant analysis (LDA).

Zhong et al. [409] proposed an enhanced time-resolved fluorescence imaging method for forensic document examination applications. In the method, a dual-gated intensity-correlation enhancement algorithm was developed. Compared with traditional rapid fluorescence lifetime determination imaging method, this method focused on improved image contrast and effectively removed background noise. In their proof-of-concept testing, three brands of highlighters of the same color were chosen and shown to exhibit fine fluorescence differences. The simulation and experimental results prove that the method can improve the ability of time-resolved fluorescence imaging.

Bomhardt et al. [410] applied soft Desorption/Ionization induced by Neutral SO2 clusters (DINeC) in combination with mass spectrometry (MS) for the investigation of highlighter inks with respect to chemical composition and the identification of different types of degradation.

Dasena et al. [411] proposed a method to differentiate pen ink colors based on normalized color histogram distance. Seven blue and seven black pen ink samples on paper cheque-stock were assessed. Threshold of distances (to decide whether a pair of words are written by the same pen or not) is identified using an optimization function. These thresholds are used for quantitative analysis of capabilities of color models for pen ink differentiation in handwritten documents. The YCbCr colour model was identified as a better colour model than an RGB color model for this task. MLP classifier then used these statistical features to differentiate whether a pair of words are written using the same pen or different pens.

Corradini et al. [412] created a reference tool for the identification of pigments using reflectance spectroscopy (in both visible and near-infrared intervals), Fourier-transform infrared spectroscopy (in both attenuated total reflection and reflection modes), and Raman spectroscopy.

From the standpoint of preservation and historic analysis, the following articles presented valuable information that can be applied by the FDE in the examination of inks.

Ali and Henin [413] conducted spectroscopic analysis of vintage hand-colored photo postcards, to both acquire knowledge on the materials and techniques used to develop an understanding of their deterioration paths; and accordingly, make correct preservation choices. Using a USB digital microscope, the photographic process used was identified as silver gelatin. Further analyses were performed using scanning electron microscopy with energy-dispersive X-ray spectroscopy, attenuated total reflectance—Fourier transform infrared spectroscopy and Raman spectroscopy to reveal the presence of Hematite, Cobalt Blue, and Naples Yellow.

Ridolfi [414] provided an outline of an exercise related to the reproduction of the pigment and natural binders used in historical illuminated manuscripts. The exercise introduced the microscopic examination of modern pigments and how they differ from historical, hand ground pigments derived from mineral and natural pigments. The preparation of natural binders derived from egg white and egg yolk was detailed, as were observations of the relative utility of these natural adhesives for pigment vs. gold inlay application to art paper.

Luizar Obregon et al. used X-ray fluorescence elemental analysis characterize the composition of inks in South American manuscripts from 1799 to 1825 [415].

Capone et al. used Raman and Principal Component Analysis (PCA) to determine if the Artemidorus papyrus was written over three different eras, based on the inks used on this document [416].

Idjouadiene et al. determined the ink and pigment composition of nine old Algerian manuscripts through several non-invasive techniques such as X-ray fluorescence, fiber optic reflectance and Raman spectroscopy. The authors identified several ancient inks, including iron gall ink and ivory/bone black, as well as one made from burned sheep wool [417].

Parker et al. demonstrated a new computational approach that captures, enhances, and makes visible the characteristic signature created by carbon ink in micro-computed tomography [418].

The article by Espina et al. focused on using different spectroscopic methods (Raman, SERS, and IR) in order to differentiate structurally related gallnut polyphenols tannic acid, gallic acid, pyrogallol, and syringic acid, components in iron gall inks [419]. The different functional groups existing in these molecules and their spatial distribution led to slight changes in their spectra.

Fierascu et al. [420] studied the potential use of non-destructive and

non-invasive techniques such as optical microscopy, X-ray fluorescence, Infrared microscopy, and Raman spectroscopy. It also proposed methods to evaluate the general characteristics such as surface pH and UV photography. Three types of inks were identified on the paper sample: a light faded black ink, a black ink, and a red ink. In the red ink, cinnabar was identified as the main pigment with traces of lead red. The black ink was identified as printer's ink. The faded black ink was believed to be iron gall ink with added carbon. The multi-technique approach revealed details regarding the inks used such as the use of mixed recipes and the presence of multiple pigments.

### 4.3. Printing technologies

Determination of printing technology may be used to confirm or refute links between devices, and even owners and places of production of documents, and so forms another problem set for study comprising four textbooks [441–444]. The following subsection on Conventional Printing comprises 26 articles [445–466], while the subsection entitled 3D Printing includes six textbooks [467–472] and four articles [473–476]. There are 23 conference presentations added in reference only [477–499], as well as three workshops which covered applicable information [500–502].

One text published in 2019, the Handbook on Printing Technology, 4th Revised Edition [441] details printing methods and applications, providing readers with a firm grasp of printing technologies in general, including revolutionary new technologies, billing itself as the only complete handbook on the commercial production of printing products. A second general book of that is essential reading for any forensic document examination laboratory that conducts analyses of printed documents of all kinds is The History of Desktop Publishing by Romano and Mitrano [442]. This encyclopedic text details the history and evolution of document production.

Carbon Transfer Printing is a text [443] about one of the earliest photographic processes that provided the first permanent printing methods. This book reviews the extensive history of carbon transfer and related pigment processes and provides new, as well as previously un-published material and techniques, such as about pre-sensitizing carbon tissue with newly identified compounds, information on the safe use and disposal of hexavalent chromium compounds, and simplified methods of producing three-color carbon prints.

Another comprehensive text of value to the FDE is Kuznetsov's Principles of Image Printing Technology [444]. This text offers a review of technology use in the printing industry since the beginnings of printing, providing a historical review of the advancement of technology and describes in-depth both technical fundamentals and industrial procedures. As this text is intended for students in graphic arts programs, it is well-laid out for the forensic community that requires the necessary background for understanding printing technologies.

#### 4.3.1. Conventional Printing technologies

Classification of 27 models of inkjets from HP, Canon, and Epson, based on image quality metrics of few letters and statistical properties of the grey level co-occurrence matrix (GLCM) was attempted by Xiao-Chen et al. [445]. The result of the classification by a KNN analysis was as high as 98% and the evaluation of the LR was significant. Their method was able to find a specific inkjet from even a few letters in the printed document.

Ma et al. [446] used the bidirectional printhead dividing line or nozzle occlusion marks combined with the maximum gauge of the printhead to determine how many times a document was printed.

Tomar et al. [447] proposed a chronological overview of analytical techniques in the forensic identification of printing toners. A critical discussion on the trends, advances of analytical techniques implemented in the past four decades, and their respective edge over each other was presented in the study. This article included analytical methods such as spectroscopic, microscopic, and chromatographic techniques for the examination of printing toner, and studies focusing on the physical and optical examination of toner and printed document were also presented. Most studies showed the efficacy of ATR-FTIR in identifying the binders present in toners. Raman spectroscopy has been largely employed to identify the type of pigment used in the printed sample. Techniques like SEM-EDX, XRF, LIBS, LA-ICPMS, etc. Were used for the elemental profiling of the toners. Recent literature shows the advent of techniques that are non-destructive, require nil to minimal sample preparation, and sustain the integrity of the sample as evidence. Another significant development is the use of data fusion techniques and chemometric methods to enhance the discrimination and identification of the sample.

Aginsky [448] used optical methods, solubility tests, and thin-layer chromatography to determine whether two documents from a real case, were printed with the same toner. The extractability in chloroform of the two toners was significantly different, suggesting that the chemical composition of the two toners was different. In this case, solubility tests were more discriminating than the optical and TLC methods.

Li et al. evaluated the possibility to distinguish laser printed documents using 33 feature parameters in a quantitative examination based on image physical metrics [449]. In this paper, printed documents from 14 laser printers of five brands were studied, and 33 characteristic parameters used to describe the printed character's area, grayscale, line/edge, and connectivity were measured using ImageXpert. The discrimination ability of 33 characteristic parameters to the printed documents was sorted by the random forest algorithm. Results of the study showed that the different brands of printers used in the experiment could be distinguished according to these 33 characteristic parameters, and most of the different models within the same brand could also be distinguished.

Polston et al. [450] analyzed the influence of hysteresis and other induction spatial effects on magnetic flux measurements of toner-printed documents. Documents of five different printers were analyzed. Measurements were conducted for each document, in four different orientations at five different locations, with 30 replicate measurements by spot. To evaluate the impact of hysteresis effects and induction current orientation effects, they used a one-way and two-way ANOVA (analysis of variance). The results showed that both have an impact on the variations in magnetic flux measurements. To overcome a part of this issue, the authors suggested to adjust the sampling methodology by rotating the sensor by 90° throughout the sampling process and collecting an adequate number of replicate measurements.

Kumar et al. [451] analyzed toners and inkjet inks by ATR-FTIR and used a chemometric approach to determine whether it belongs to the laser or inkjet or photocopier devices. FTIR spectra were pretreated with a SNV (standard normal variate) algorithm before that a PCA (principal component analysis) and an HCA (hierarchical cluster analysis) were applied. This approach is promising for the classification of laser or photocopier devices but not for inkjet as it is possible to differentiate them by a simple optical analysis.

In their study, Salim and Abdalla determined the source of color laser machines from their printouts [452]. The team examined 400 color laser printout samples from 93 Ricoh® different color laser printers using three defined steps (printing, scanning, extracting) were to measure and calculate the data. Adobe Creative Cloud Photoshop 2018 was used as a forensic tool for image processing. The study results successfully present the basic coded dot matrix pattern (CDMP) that characterizes and corresponds to the Ricoh® color laser machines with a 100% accuracy ratio.

Joshi et al. developed a source printer identification method based on the hypothesis that the printed letters exhibit location-specific variations due to the electrophotographic printing process's characteristics [453].

Jain et al. [454] proposed a set of features for characterizing text-line-level geometric distortions and presented a novel system to use them for identification of the origin of a printed document. Detailed experiments performed on a set of 14 printers demonstrated that the

proposed system achieved good performance and much higher accuracy under small training size constraints. For example, a classifier trained using one page/printer/font with three different fonts and 14 printers achieved 98.85% average classification accuracy.

According to Joshi and Khanna [455], the development of automated systems for classifying printed documents based on their source printer, using image processing techniques, is gaining a lot of attention in multimedia forensics. Current systems require that the font present in the questioned documents of unknown origin must be available in those used for training the classifier. In this paper, the authors attempt to overcome this limitation by introducing a novel printer specific local texture descriptor (PSLTD) with an encoding and regrouping strategy which enhances its discriminative power.

In this study, Li et al. [456] determined the stability and specificity of a counterfeit protection system (CPS) code. This research involved the analysis of a counterfeit protection system code unit over time using the pattern location measurement method. Four types of characteristics were established: CPS pattern unit, distance of the CPS unit, position of dots, size, and shape of the dot. Except for the partial changes in the Xerox brand, no other brand exhibited changes over time, implying that the CPS characteristics are stable.

To determine whether an individual repeating pattern unit could be obtained to identify the classification of printed color laser documents, Li et al. used a pattern location measurement method [457]. In their study, four class characteristics were used to identify the print source: (i) the relation between the pattern and print output direction; (ii) observation of the shape features from among the trace code pattern units; (iii) the feature arrangement from among the trace code pattern units; and (iv) the arrangement relation of the trace code pattern.

In their paper, Hamzehyan et al. presented a new method for printer source identification by using the basic features of the printing textures and refining them with the joint factor analysis technique [458].

Gupta and Kumar used a document classifier model to efficiently classify questioned documents to their respective printer class, with adaptive boosting and bootstrap aggregating methodologies used to improve classification accuracy [459].

Continuous inkjet printing relies on steering charged droplets accurately to the surface by using electric fields [460]. In this paper the authors study the build-up, or unwanted deposition of ink on the deflecting electrodes. They report a laser-based high-speed visualization technique to observe build-up and show that it stems from small satellite droplets that break off from the main printed drops. The material build-up was characterized, revealing its nanoscale particulate nature.

Asri et al. were able to discriminate inkjet, laser and photocopier printed documents using Raman spectroscopy and chemometrics [461]. This article proposed the use of Raman spectroscopy combined with Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) to differentiate printed documents from different technologies. The chemometric approach used in this study showed a potential for the classification and individualization of printed documents, and the Raman spectra yielded unique peaks with specific functional group each for each category of laser, inkjet and photocopier with all samples were correctly classified.

Takaoglu and Takaoglu conducted a mini survey on printer steganography in their yellow dot analysis [462].

Source printer identification can be a challenge in forensic document examination [463]. In their study, Joshi et al. proposed a method whereby source printers are identified from document images acquired via a smartphone. The authors proposed using a single CNN model from the fusion of letter images and their printer-specific noise residuals. They created a new dataset consisting of 2250 document images of text documents printed by eighteen printers and acquired by a smartphone camera at five acquisition settings. The proposed method achieved 98.42% document classification accuracy using images of letter 'e' under a '5 2 cross-validation approach.' Further, when tested using approximately half a million letters of all types, it achieved 90.33% and 98.01% letter and document classification accuracies, respectively.

Mishra et al. [464] reviewed the issue of examiner opinion when only photocopier reproductions of documents are submitted for examination. A case study was presented to emphasize that forensic document examiners need to express whatsoever opinion is possible using the photocopies submitted for examination, in case the originals are not forthcoming, so that their opinion evidence, however insignificant it may appear to be, can be considered, and acted upon by the courts of law in corroboration with other evidence and overall facts and circumstances of the case.

Tsai et al. [465] worked to develop a system whereby Convolutional Neural Networks (CNNs) of deep learning were used to identify the source printer for text and image documents. For printed documents, feature based SVM systems outperformed the deep learning system with limited gap, whereas for scanned documents, both systems achieved equally well with high accuracy.

Gál et al. [466] investigated the application of non-destructive method including FTIR spectroscopy in combination with principal component analysis (PCA) and multivariate analysis of variance (MANOVA) to differentiate black laser prints. A set of 49 types of laser printers of ten brands was investigated. PCA was applied to identify the differences between the laser toner samples. PCA of laser prints spectra was used as a base of the method for toner identification. The difference between the spectra of the unknown print and the spectra from the database was tested. A document printed on three different printers was prepared to evaluate the method; a MANOVA test together with a PCA scatter diagram confirmed that this document was printed on three different printers.

#### *4.3.2. 3-D printing technologies*

As a technology 3-D printing has become mainstream. Since FDE have extensive knowledge about printing technologies of all sorts, from their earliest iterations to present day novel technologies, the examination of 3-D printers has become part of the repertoire of many forensic document examiners, and thus warrants a subsection in this review. While this section is far from complete with respect to 3-D technology, it does provide some coverage of the topic from which to build.

Several textbooks were published during the review period on the topic of 3-D printing. Awari et al., Mendis et al., Dave and Davim, Torta and Torta, Horvath and Cameron, and Muralidhara and Banerjee, compiled texts that cover many aspects of 3D printing, from a complete introduction of the technology to additive manufacturing and 3D printing technologies and methodologies to intellectual property and regulation. These textbooks provide the reader with good foundational knowledge in this new technology which serves to assist the forensic document examiner in their knowledge of this printing technology [467–472].

Aronson et al. [473] linked 3D Fused Deposition Modeling (FDM) printer using Polylactic Acid (PLA) filament to printed objects by using stereomicroscope and comparison microscope. They compared marks on the base face of the printed object and marks found on the 3D printer's heated stage.

Brinsko-Beckert and Palenik [474], to determine their morphology and chemical features, analyzed the dust particles produced during the printing process. The aim of the study is to detect, recognize and identify the dust particles from 3D printer. To proceed, the authors tested different instruments. The samples used were the dust produced by thermoplastic filaments, composed of acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). ABS particles were mostly large while PLA particles were small. ABS particles were recognized using stereomicroscope or polarized light microscope by their morphology, optical properties, color, and fluorescence while PLA particles were observed by FE-SEM-EDS. To identify the polymer, Raman and FTIR were used for ABS as particles are large, while Py-GC/MS is necessary when the particles were smaller as for the PLA ones. Authors suggested that other features should be investigated to discriminate filaments and the dust

particles produced by them as pigments, dyes, fillers, additives, or inclusions.

The first part of the study of Trincat et al. [475] could be interesting for Documents experts. 3D-printed pieces and the traces present on it were analyzed to obtain information about the printing process, the 3D-printer, the printing parameters, and the polymer used. 36 Liberators were 3D-printed using 4 different printers with three different printing processes (2 based on principles of Material Extrusion, one on Vat Photopolymerization and one on Powder Bed Fusion) and 11 polymers were tested. The examination of the pieces allowed the authors to determine the printing process used and some printing parameters, useful to determine if a given command file, slicer or 3D-printer could be at the source of a questioned 3D-printed part.

A review and assessment of 3D printer engineering features and the materials used was presented in the article by Day et al. [476]. This paper provided an understanding of the potential application and development of forensic techniques used to identify a 3D printer source and the comparison of printed materials that may have been used in alleged criminal activity.

As previously stated, the reference section for printing technologies includes many references [441–502].

### 4.4. Stamps and Stamp Inks

Stamps have been in use for thousands of years for all forms of business and social use and continue to be important globally in travel and identity documents, as well as regionally with course-of-business documents, Over the period of this review 11 articles [503–513] have been published on this topic, as well as seven conference presentations [514–520].

Li and Hui [503] analyzed several reproduced stamps from different manufacturers to document a better understanding of common practices in stamp manufacturing and in particular, how the quality of the source stamp impression could affect the end product, the duplicate stamp. They compared the stamp impressions with the original stamp to determine if it could be possible to distinguish them. The comparison is based on the size and defects. To create a good duplicate stamp, quality of the source impression, scanner device and the knowledge of the manufacturer were essential. To obtain a perfect duplicate stamp, several control conditions are necessary.

Rulli et al. [504] compared measurements of stamp impressions made to different apposition and environmental conditions and found no significant differences. They concluded that: “Differences larger than 0.09 cm supported the hypothesis that two different stamps were actually used.” The difference could reach up to 0.29 cm when stamps from different manufacturers were used.

Wang et al. [505] analyzed 21 stamp-pad ink by hyperspectral imaging (HSI) with chemometric approaches to classify them. From the hyperspectral images, the reflectance spectral data were obtained by pixel fusion. Principal component analysis (PCA) and non-negative matrix factorization (NMF) were tested to visualize the data, but results presented were not good. Then, back propagation neural network (BPNN) and one-dimensional convolutional neural network (1D-CNN) were tested to classify the stamps. 1D-CNN presented the best stability and efficiency for the classification. Classification accuracies were 98.30% for training set and 97.94% for validation set.

Sixteen brands of blue stamp inks and 12 brands of red stamp inks were analyzed using ATR-FTIR [506]. Discriminating power calculated was respectively 96.6% and 93.9 by visual comparison. PCA-LDA and PLS-DA was conducted on the data to classify the stamp inks according to their brands with good results.

Chayal et al. set out to develop a simple, rapid, sensitive, eco-friendly, and non-destructive method to identify signatures applied with rubber-stamps [507]. In this case study, spectral analysis using relatively high magnification of 164X with oblique light in angular positions was used to observe the invisible tremor strokes from the manufacturing process, and the wear and tear marks around the rubber-stamp signatures.

The article by Zubova et al. [508] outlines the characteristic features of seals, considers the conditions for the occurrence of features in the process of their use, shows the evolution of their change, outlines the time periods for the existence of features, and defines the criteria for attributing features to identify significant temporal features. For the categorical conclusion that the impression of a seal (stamp) was made at a specific time, a set of persistent individual features that appeared in the studied impression and its copy over a certain period must be established.

Chiang and Sun [509] worked to prevent stamp forgery in their article detailing anti-counterfeiting properties for stamp reproduction. They proposed two methods to obtain difficult-to-replicate dot structures and to provide corresponding color management methods.

Li and Liu [510] proposed a comprehensive examination method for signature stamps; these stamps are photosensitive seals made in the style of a handwritten signature. The authors suggested a method that includes microscopic analysis and ink composition analysis which improved the accuracy and the detection rate of the examination process. Their study collected and tested photosensitive stamp-pad inks, fountain pen inks, gel inks and erasable inks, and used infrared and fluorescence analyses and microspectrophotometry to distinguish the photosensitive ink from both erasable ink and fountain pen ink.

In their study, Wang et al. [511] explored a new method for the rapid and non-destructive identification of stamp-pad inks by combining hyperspectral imaging (HSI) technology and deep learning. The authors collected 20 different stamp-pad inks and used them to affix six seals of each on to A4 printing paper. Hyperspectral images were obtained, and the data treated with different deep learning techniques and the results compared. The combination of hyperspectral imaging technology and one-dimensional convolutional neural network 1D-CNN represented a potentially simple, non-destructive, and rapid method for stamp-pad inks detection and classification.

Sharaa et al. [512] studied the intersecting lines between stamp-pad ink and electrophotographic (toner) printing. In this study, the authors used six different brands of stamp-pad inks, toner of five laser printers of various make and model, three types of papers, two kinds of seal materials from three methods of seal manufacturing to produce the samples of heterogeneous intersecting strokes. A combination of microscopy and an analytical instrumental technique (i.e., Raman spectroscopy) successfully discriminated the sequence of intersecting strokes of toner and all brands and colors of stamp-pad inks.

In cases where multiple stamp impressions on several reproduced documents appear to have the same relative positioning and orientation to the other elements (e.g., signatory line) on the document, the document examiner must consider the possibility that these stamp impressions could either be a result of cut-and-paste manipulation (hence not a product of an inking process) or an original stamped impressions that match by chance i.e. random chance matches [513]. This proof-of-concept study examined stamp impressions made by one of the authors deliberately aligning and orientating the stamp in a specific way on a document, while considering the shape of the stamp die, stamp housing, and the presence of a signatory line. The percentage of stamp impressions that had matching relative position and orientation was found to be between 0.08 and 0.69%. This exploratory study suggested that when stamp impressions encountered in more than one reproduced document have similar placement and orientation relative to other elements in the document, the examiner must objectively consider whether they were made by “cut-and-paste” manipulations or a chance occurrence.

As with previous section, the seven conference presentations [514–520] are only included as references.

### 4.5. Substrates

Substrates, the medium upon which a document is created, cover a vast range, including but not limited to traditional paper, man-made substrates such as polymers and stone-papers, as well as mirrors, blackboards, and walls. Two textbooks [521,522], 13 articles [523–535], 12 conference presentations [536–547] had substrates as their subject in this period of review.

Bajpai published a text in 2021 giving professionals in the pulp and paper industry, as well as the forensic community the most up-to-date and comprehensive information on the state-of- the-art techniques and aspects involved in pulp and paper making from non-wood plant fibers [521]. Also published was a text by Bhat et al. on the use of nanotechnology in the paper and paper industry [522]. This text covers nano-papers and nano-woods and acts as a good reference for these recent advances in technology.

In their study [523], 24 different kinds of writing and printing papers and their compositions were characterized and discriminated by using Thermogravimetric Analysis (TGA). Although there were few differences observed on visual inspection, significant differences were obtained on the basis of their kinetic parameters. Results showed a 99.28% discrimination between all possible pairs of paper samples.

Itamiya et al. [524] analyzed and differentiated six water-soluble papers using physical analysis (grammage and thickness), X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDX) and pulp analysis by Graff “C" stain.

Lee’s study [525] evaluates the potential of using ATR-FTIR for the analysis and classification of paper samples. Results showed that solely relying on the FTIR spectrums was not enough to classify and discriminate samples, and that the use of a classification method like a regression tree (CART) was necessary.

The research by Liu et al. [526] modeled the photodegradation of 23 samples of historical rag paper under polychromatic visible radiation.

Lucejko et al. [527] explored the use of analytical pyrolysis-gas chromatography-mass spectrometry to investigate the chemical alteration pathway occurring in papyri from different historic periods and to understand the different chemical preservation states.

The study by Proietti et al. detailed the multi-disciplinary analytical characterization of handmade papers from Italy’s 13–15th centuries various analytical techniques [528].

Zamboni et al. analyzed historical photographs by pXRF, ATR-FTIR and microscopy to identify their composition. The results of the ATR-FTIR presented and the XRF used by the authors were discussed by Bittencourt Bovolenta in an online commentary to the initial article. They supposed that the binder material in photographs was probably misidentified and suggested to use a different XRF [529].

Gazy et al. conducted research is to improve the printability of papers by making modifications during the paper manufacturing process [530]. Various types of styrene-acrylate polymer latexes were used for the modification of different papers using different emulsifying agents. The results showed significant improvements in degree of gloss and ink density on the polymer-coated papers.

Chao et al. synthesized a water-based varnish to improve printability of inkjet printing papers, as well as improving water resistance, adhesion, and friction resistance [531].

Tomar et al. [532] investigated a non-destructive approach to examine thermal papers by using ATR-FTIR spectroscopy and spectral analysis, coupled with chemometrics.

Di Turo et al. [533] were able to discriminate papers used in conservation and restoration using voltammetry of immobilized microparticles (VIMP). Chemometrics allowed for the identification of the different papermaker production techniques in their samples, and the samples could be grouped according to their internal chemical differences by using the experimental. Their proposed method aimed to develop a micro-invasive method, which would allow for the chemistry and the manufacturing methods of ancient papers to be distinguished.

Zieba-Palus et al. [534] conducted a study to assist in the forensic investigation of papers. The aim of their research was to evaluate the possibility of differentiating papers by studying the specificity of their aging process. The team artificially aged five paper samples then analyzed the samples using infrared and UV/Vis spectroscopy followed by 2D correlation analysis and PCA. The results proved promising for this discrimination of papers; however, the sample size is limited.

Staskova et al. studied carbonless papers [535]. For this, the authors chose to study crystal violet lactone (CVL), the most commonly used color developer in carbonless papers. They verified that CVL exhibited different properties in carbonless paper than in office papers and monitored changes of thermal and light aging on the physical and chemical properties of copies by exploiting CVL’s ability to luminesce in the IR region. Visual, colorimetric and structure differences between the copies made on the carbonless and the office paper were analyzed.

The 12 conference presentations included in references [536–547] for this section are not expanded upon here.

### 4.6. Document dating

Determining the date of production of a document is still one of the most common, and oftentimes the most difficult problems encountered by the FDE. There are two main approaches to date determination: the Static approach is the most straightforward. This approach is used to solve dating problems by determining the dates of production or introduction of the technologies used to create documents, or components of documents. For example, if the materials or instruments used to produce a document were not available when a document was purported to have been produced, this is anachronistic. Another word used to describe this is Absolute Dating.

The Dynamic approach takes into account certain features of a document that evolve or change over time. Here think about trash marks on documents from dirt on a photocopier, or a worn portion of a rubber stamp, or components of ink that change over time. Another word to describe this is Relative Dating. And finally, another aspect of Relative dating is to determine the chronology or sequence of events which may prove useful to date a document in a relative sense. Alterations, sequence of stroke determinations, and page substitutions are all examples of ways to date documents with respect to other events.

The FDE can examine all parts of the document in their assessment of potential date of production, including handwriting/signatures, inks, and toners, writing instruments, stamp pads, printers and printing techniques, paper and other substrates, and other related materials, such as correction fluids, ribbon inks, etc. including any other technology used to prepare the document. The following 64 articles [548–580] [581–611], combined with 17 presentations [612–628] at conferences shows level of research activity around this analytically challenging topic.

Kapoor et al., in their article [548], conducted a review of different approaches to date a document; they term the three main categories the static approach, dynamic approach and supplementary approach. The authors provide descriptions of these methods, the latter being the supplementary approaches which include accelerated ageing techniques, chemometrics, constructing the chronology of documents, analyzing luminescent components, radiocarbon dating and nanotechnology-based methods.

A significant challenge in document dating is the determination of the sequence of crossed lines of inks, or toners, or both. The following articles discuss various research into this topic.

The team of Mathayan et al. conducted a study of the intersections of ballpoint or gel pen inks with toner or inkjet printed lines [549]. They combined micro-Rutherford backscattering spectrometry (micro-RBS) and particle-induced X-ray emission (micro-PIXE) mapping of the intersections to study the depth distribution of chemical elements in plain paper and inks/toner deposited by different pens as well as inkjet and

laser printers. This study assisted in identifying under which conditions the sequence of inks deposited could be reconstructed.

Several teams studied intersections between toner printed lines and inks of various kinds. Chai and Li [550] wrote about the factors that influence sequencing between inks and toners. Shraa et al. considered non-destructive techniques to detect the sequence of crossed gel pen ink with toner printed strokes [551] A more refined study by Shraa et al. [552] then considered the physical and chemical characteristics of specular reflection, ink gloss, ink spreading and gap, using Raman spectroscopy and microscopy. Wu et al. used laser fluorescence microscopy to study the intersections between stamp ink impressions and toner printing [553]. And in 2021, another study of stamp ink impressions and laser-printed lines focused on the characteristics of the toner fusing characteristics [554]. Wu et al. [555] studied the use of coaxial lighting to view the sequence of line crossings between electrophotographic processes (toner) and writing inks. The team of Binette et al. used Mikrosil™ casting of the intersection of toner-printed lines with blue ballpoint pen ink lines to determine the sequence of strokes [556]. Finally, Esmaeili et al. [557] investigated the use of Color Measurement Technique to sequence the intersections between laser-printed lines and handwritten ink lines.

Zhang et al. [558] used Optical Coherence Tomography in an initial study to determine the sequence of strokes between gel pen ink and stamp ink impressions. Rodrigues de Morais et al. [559] showed that mass spectrometry imaging (MSI) coupled with easy ambient sonic-spray ionization (EASI) could be used to accurately identify the sequence of lines at intersecting points between stamp and pen inks.

The study by Rodrigues e Brito et al. described the use of Raman hyperspectral imaging with different chemometric techniques for the objective determination of the chronological order of 56 blue and black gel pen ink line crossings [560]. A further study by Rodrigues e Brito et al. [561] evaluated the potential of using near infrared hyperspectral imaging associated with multivariate data analysis for the discrimination of intersecting ink lines.

Kaur and Kaur also tested optical methods to determine the chronological intersecting sequences between toner and pen inks (ballpoint and gel pens) in homogeneous and heterogeneous cases [562].

Barac et al. [563] studied intersections of inks from different writing instruments (i.e., ballpoint pens, a fountain pen, and a stamp) using a comparison of optical techniques and Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) using MeV ions. According to the authors' research, as a technique MeV SIMS proved to be more efficient for oil-based inks while difficulties were encountered with water-based ones, like with optical methods.

Almeida et al. [564] proposed a non-destructive method for the characterization and order of ballpoint pen ink line crossings. They used laser desorption ionization mass spectrometry (LDI-MS) and LDI mass spectrometry imaging (LDI-MSI) to determine specific information on the chemical composition of the material without destroying the spatial location of the components, thereby allowing for sequencing of the strokes.

Sabater et al. [565] presented a combined method using infrared reflectance photography with luminescence, fluorescence micro-spectrophotometry, Fourier transform infrared spectrometry, high resolution liquid chromatography and gas chromatography with mass spectrometry to distinguish ink strokes made with ballpoint pens. This study used a control group of freshly made ink lines with an intersecting stroke that was written four years prior. Neither luminescence infrared reflectance measurements, nor fluorescence micro-spectrophotometry allowed the authors to determine the order of strokes FTIR analysis of samples distinguished older samples from recent ones in intersecting ink strokes based on the number of hydroxyl functional groups (−OH), but interference with certain components of the paper proved problematic. Both HPLC-DAD and GC−MS were able to differentiate the relative concentrations of dyes and solvents in both intersecting lines which, according to the authors allowed for the determination of oldest ink, and if they were made at different times.

Determining the sequence of printing and writing is that much more difficult when there are no intersecting lines to examine, although this problem is often encountered. Gupta and Saini [566] determined the chronological order between toner printing and gel pen writing by examining the pattern of toner distribution, ink distribution, and fiber distribution on sample documents. To determine the chronological order, three micro-conformation features were analyzed: the ones of toner distribution, those of ink distribution and those of fiber distribution. For the toner, shape, and appearance of particles as the sheen on them were observed. For the gel pen ink, it was the edges of the stroke, the regularity of the ink distribution and the fading of margins of the stroke, the smooth margins and the stoke. Concerning the paper itself, the groove and the fibers were observed, especially if some fibers were raised or if they were on the same plane. The authors highlighted that if the printing was made with black toner and the gel pen ink color was black, no result was found. By studying 300 samples, their results demonstrated that this method could successfully establish the sequence that the document was printed, and the gel pen ink written.

The analysis of inks to confirm or refute the proposed age of a document has long been a subject of study in forensic document examination. This study, commonly called 'ink-dating' is the subject of many of the articles in this review section.

Gorziza et al. [567] conducted a ten-year systematic review of ink dating approaches for blue and black ballpoint pen inks, recognizing that while the methods published to date offer relatively good accuracy, further research is required to consider such topics as document storage conditions, the influence of initial ink quantity variation between different pen brands and by different writers, and the type of paper.

Bello de Carvalho et al. [568] performed HCA and PCA on blue and black ballpoint pen ink FTIR spectra. Firstly, 37 blue and 27 back inks were analyzed. Spectra were pretreated (smoothing and normalization) then HCA and PCA were performed to group them by brands/models. Afterward, they evaluated the influence of the support paper in the spectra of ink and concluded that there is no effect for five different papers. In the third part of this paper, ink spectra obtained directly from the pen cartridge and those obtained from lines on papers were compared and no difference were observed by the authors. Finally, spectra of eight blue and six black pens applied recently and after some days to some years were analyzed and PCA was applied to date the writings. The authors concluded that this technique was promising.

Lyter [569] analyzed Phenoxyethanol (PE) standard solutions by GC/MS before and after various routine maintenance to address the impact that various instrumental conditions and parameters could have on the ability to measure the quantity of semi-volatile components accurately and precisely. Instrumental components ranging from the injector, through the column, to the source were evaluated; the author determined that the instrumental parameters tested had no impact upon the measurements of PE.

Gorshkova et al. [570] used Raman spectra for dating documents written with pen composed of triarylmethane dyes. They identified temporary markers (Raman bands) of a set of five writing inks, bands corresponding to dye degradation. They used PCA (principal component analysis) to separate inks into groups that correspond to different creation intervals.

In their research, Leal et al. [571] developed analytical methodologies to determine of the time of ink deposition through the characterization of the dyes' chemical changes. Based on their preliminary chromatographic results, it was not only possible to discriminate a liquid from a viscous ink, but also to distinguish the time since deposition for the viscous inks. Qualitative and quantitative chemical information of the different dyes in ink was obtained and used to date the inks.

The known method of ink dating by 2-phenoxyethanol analysis has been the subject of much research to improve sensitivity and accuracy of the method. One such study by Leal et al. [572] set out to determine if derivatization with a silylating agent/catalyst combination of MSTF:

TMCS would increase the sensitivity of the method, thereby allowing for the estimation of the ink age for a longer period.

The team of Mouquinho et al. [573] set out to develop analytical methodologies that allowed for the determination of the time of ink deposition through characterization of chemical changes in dyes.

Using high-performance liquid chromatography with diode array detection (HPLC/DAD), the team was able to discriminate between liquid or viscous ink from analysis of the chromatograms and spectra. Their method, still under development, proposes that it is also possible to determine the time of deposition of the viscous ink.

Hoang et al. [574] combined green and traditional methods to improve accuracy in the estimation of relative and absolute age of ballpoint pen inks. Green methods like Raman and paper characteristics measurement were used to first determine batch similarity and storage conditions of the documents and inks. This information was then used to interpret the HPTLC results (Rf and color intensity) to establish relative dating.

In their study, Ouyang et al. [575] used the absorbance ratio method to determine the age of an ink-stamp impression. The extraction solution of the stamp ink is analyzed by UV–Vis spectrophotometer after 3 min and 30 min to obtain the absorbance ratio. The authors concluded that this was a suitable method to determine the relative dating of ink-stamp impressions provided that they were affixed to a document within ten weeks. However, certain conditions must be met; for both the stamp inks and the papers, the requested and the comparison should be the same and the storage conditions should be the same. This method could also be applied when comparing two seals supposed to be stamped at the same time on the same sheet of paper.

Salkım İşlek et al. [576] reported a case study of ink dating. They analyzed ballpoint pen inks by high-performance – liquid chromatography (HPLC) and thermal-desorption gas-chromatography/mass-spectrometry (TD-GC-MS) to determine rate of demethylation of the colorant Crystal Violet and the evaporation of the solvent Phenoxyethanol.

Ortiz-Herrero et al. [577] investigated non-invasive methodology for dating ink of both gel pens and ballpoint pens. The team first captured ink spectra using Vis-microspectrophotometry. Ink clustering and classification was then conducted using Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), to determine the optimal orthogonal partial least squares (OPLS) model to predict the ink's age. Their results showed an effective technique able to predict the aging process of the dyes present in inks, up to two years after the time of deposition of the ink on the paper.

Goacher [578] used Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) in her investigation of the intersecting strokes from a single black ballpoint pen ink on a document to obtain both a relative dating and an absolute dating method for these self-intersecting lines. She concluded that within the first six months, there were significant changes in the surface chemistry of the intersecting lines with smaller changes occurring up to 22 months from ink deposition. For the three inks tested the author found this method allowed for relative dating after a six-month analysis delay.

Gas chromatography – flame ionization detection (GC-FID) was used to quantify triethylene glycol (TEG) from three carbon-based black gel ink strokes. By this method, the authors were able to distinguish questioned ink sample less or greater than nine months based on the content of TEG in ink strokes [579].

Łydżba-Kopczynska et al. [580] applied chemometric methods for the rapid, non-destructive determination of fading and age determination of blue ballpoint inks. This study set out to determine the applicability of micro-Raman and VIS–NIR reflectance spectroscopy in classification and age determination of 74 blue ballpoints inks containing phthalocyanine and crystal violet. The first set of samples was stored for seven years at room temperature without direct exposure to the light. The second set was aged by exposing them to a natural light cycle for 85 days. The results of this study confirmed the potential of the method.

In their work to determine aging of documents, Baygildieva et al. re-evaluated the process of artificial ageing used to mimic the effect of storage on a document [581]. Their work concluded that artificial ageing using UV light cannot simulate the process of natural ageing, due largely to the many different variables with the natural ageing process.

Santos et al. [582] used an alternate method to monitor dye degradation in their attempts to determine the date of production of documents. Their work proposed the application of a multivariate regression model based on image data to monitor this decolorization process in the dyes. They compared the results from their method on data from both digital imaging and UV–Vis and found them to be comparable.

Li conducted an in-situ study of the diffusion kinematics of stamp impression inks by micro-infrared spectroscopy to better understand the diffusion behavior of these inks over short time periods [583].

In another study, Aginsky [584] described a microscopic method for determining the average size of toner particles used to produce a printed document. This characteristic could be used in substitution cases or to detect anachronism.

To determine if a document was printed in one go or not by the same printer, Ma et al. [585] analyzed the effect of repeated fusing on toner using microscopy. Micrographs of toner become brighter, darker or both with repetition of the fusion process. The authors calculated the average gray value of the micrographs of toner to determine if there were repeated printings on the document. For some laser printers, this process was conclusive. If this kind of lack of consistency is highlighted on a document, repeated printing on the same page could be the cause.

Carbon free carbon copy paper is a special chemical pressure sensitive material on which to write, used often in China for business documents [586]. Feng proposed an experimental analysis based on the "fading" gray value measurement method to determine when handwriting was executed on this type of paper. In this paper, the characteristics of the solvents and colorants for pens and their influence on the formation of handwriting are analyzed. It was concluded that the types of solvents and colorants in both the pen ink and from the carbon free copy paper have an impact on the ability to date writings on this paper.

Ornato's study reexplored the idea of dating a document through its watermark [587]. The efficacy of this method is a based on the objective criteria of length of time the watermark was in service and the duration of the 'consumption cycle' of the paper produced from it. It is possible to date using watermarks and the older the watermark the more likely it was to be dated. The drawback to this method is the requirement for a large library of known watermarks with dates of introduction to be able to compare to the questioned watermark.

Silva et al. [588] studied the application of infrared spectroscopy for document dating. In this paper the authors evaluated the complexity of infrared spectroscopy and chemometric approaches, showing that since the degradation of paper depends on several factors, these methodologies must be carefully evaluated before being used for forensic purposes.

Basta et al. [589] investigated a new methodology to examine and date printed documents, involving the use of machine identification code (MIC) from printers and UV fluorescent ink in the printing process. Their approach could assist workers in examining questioned document by specifying the authorized date and position of printed documents from the MIC.

A study by Botti et al. offered a non-destructive method to date paper using spectroscopic methods by comparing their degradation processes [590]. The focus of this study was to find ageing markers based on variations of Raman and fluorescence spectral features. As paper samples of different ages undergo different chemical ageing process, the proposed diagnostic protocol is based on Raman and luminescence spectroscopy combined with morphological analysis to obtain 2D chemical mapping across the whole page.

A final category of document dating that was the subject of numerous articles dealt with historical documents and their components.

Omayio et al. conducted a comprehensive review of historical

manuscript dating approaches and techniques from traditional to modern (computer-based) methods [591].

Pigorsch et al. [592] dated starch in the paper by radiocarbon measurements using accelerator mass spectroscopy. They used 50 paper samples of known production year from 1950 to 2018. The differences between the calibrated ages and the actual harvest years of the starch containing plants were up to three years. The authors considered that: "the potential difference between the date on a questioned document and the actual year of production of the used paper can be only 1–5 years."

Ding et al. [593] evaluated the use of solid phase microextraction combined with gas chromatography-mass spectrometry (SPME-GC/MS) to assess the degradation Chinese traditional handmade papers. The team gathered handmade papers from three different provinces in China for this study. They identified the volatile organic compounds (VOCs) emitted by the papers, evaluated the effect of artificial ageing of the samples on the volatile organic compounds.

Calà et al. [594] identified possible forgeries in historical documents using non-destructive and micro-destructive methods. Studying mainly the ink and dyed threads on the Privilegium maius, the team used Fiber Optics Diffuse Reflectance Spectroscopy (FORS) analysis to distinguish the types of black ink present. Most of the document was written using iron gall ink, but other different inks were identified as well. The dyed threads were analyzed using FORS and molecular spectrofluorimetry with fibre optic (FOMF) and then with micro-invasive techniques to determine when the threads were dyed.

Titubante et al. [595] proposed a multi-technique approach to characterize both paper and ink in a non-destructive way. The authors used the analytical chemistry techniques of Infrared Reflectography, X-ray fluorescence and colorimetry, High Performance Liquid Chromatography with UV/Vis detection and Fourier Transform Infrared Spectroscopy to classify both the papers and inks based on their chemical compositions.

Oubelkacem et al. [596] investigated ancient parchments by means of completely non-invasive multi-techniques analysis combining elemental X-ray Fluorescence (XRF) and structural/molecular Raman, Attenuated Total Reflectance - Fourier Transform InfraRed (ATR-FTIR) and Fiber Optics Diffuse Reflectance (FOR) spectroscopies besides pHs and colorimetric measurements. Their results add to the body of knowledge about genuine ancient parchments of this historical time and location.

The publication by Bausch et al. sought to highlight the effects of light-induced degradation of papyri and to facilitate an understanding of the underlying aging mechanisms. Although this accelerated aging study supports future conservation measures, its application to forensic science is equally valuable [597]. Another study [598] explored the non-destructive application of ATR-FTIR combined with chemometrics to discriminate ancient papers.

One study aimed to explore a model for estimating the age of seal ink impressions from paintings and calligraphy [599]. The authors used changes in the reflectance spectra by heat-aging on seal samples to establish a spectral heat-aging model that can be used to estimate the aging times of seals.

Another study presented a method to date documents based on the spectral response of iron-gall ink at different wavelengths over time [600]. In this work, the authors investigated a new content independent and non-destructive approach based on multispectral imaging combined with a ranking classification technique, to track the spectral responses of iron-gall ink at different wavelengths overtime. This method was evaluated using handwritten letters dating from the 17th to the 20th century; their experimental results demonstrated the effectiveness of this technique.

Ghigo et al. offered a simplistic, non-destructive approach to characterize the composition of ancient black Egyptian ink, thereby allowing for attribution of the document to a certain time [601]. Goler et al. also studied papyri documents from Ancient Egypt, using Raman spectroscopy and linear regression of pigments to date them [602].

Perruchini et al. explored ways to identify compounds characteristic of ingredients used in the manufacture of traditional Chinese inksticks used on manuscripts [603]. Neugebauer et al. worked on the non-destructive or minimally invasive analytical identification of pigments in works of art for dating purposes in authentication cases as well as under preventive conservation aspects [604]. Moretti et al. identified the composition of historical felt-tip pen inks from the 1960s [605].

Schuetz et al. [606], working on the Dead Sea Scrolls, sought methods to date a document using only non-destructive methods as to not alter with the archeological document. Their findings showed that micro–X-ray Fluorescence (μXRF), Energy Dispersive X-ray Spectroscopy (EDS), and Raman/FT-Raman were used to identify which both components of the parchment layers and contamination on the documents.

Fedi et al. [607] set out to carbon-date accurately the ink on a document even if the substrate is older, as it may be more accurate to use the ink for this dating technique with the assumption that it is more plausible that the ink was created closer to the production of the document rather than the paper substrate (i.e., papyri). They extracted the ink in two baths, then used FTIR to ensure no residue of the substrate in their analysis before conducting the carbon-dating.

To satisfy the requirement to be non- or minimally destructive in the analysis of ancient documents, Kasso et al. tried to establish a new method for carbon-dating which would allow for smaller samples to be analyzed [608]. They found that the Elemental Analyzer combustion and automated graphitization method worked significantly better for smaller samples (i.e., 0.3 mg) while keeping an accurate age reading.

Solis et al. also worked with carbon-dating analysis in their study of Mayan Codex to specifically compare extraction methods for increased efficiency in their analyses [609].

The bomb peak represents an excess of carbon-14 ($^{14}C$) in the atmosphere, caused by nuclear weapons testing during and after World War II which nearly doubled the concentration of $^{14}C$ in the atmosphere. Analysis of this period by carbon-dating results in a peak called the bomb peak. The team of Hajdas et al. [610] proposed a method which uses the bomb peak to confirm the authenticity or forgery of different artwork on paper media.

A final study of interest in this section considered handwriting evolution as a feature for document dating [611]. In this study, the development of handwriting styles over time in the Dead Sea Scrolls, a collection of ancient manuscripts, was used to create a model to predict the date of a query manuscript. The date estimation from grapheme-based technique outperformed other feature-extraction techniques in identifying the chronological style development of handwriting in this study.

The 17 presentations delivered at conferences on the topic of document dating are included in references only [612–628].

### 4.7. Document Recovery

This holistic term is being used here to include the various means by which documents can be damaged and the corresponding ways FDEs employ to recover the information from those documents. This section is subdivided into three headings: Alterations and obliterations, charred and fluid-soaked, and reconstruction.

#### 4.7.1. Alterations and Obliterations

Alterations and obliterations are ways in which documents can be changed, however the connotation is not necessarily nefarious. Ten articles [629–638] and three conference presentations [639–641] comprise this review.

Purba M. K. and al [629]. analyzed alterations, obliterations and additions made with pens (ballpoints, gel pens, fountain pens) using hand lens and oblique, transmitted and UV light sources. They also analyzed the composition of the pens using SEM/EDX.

Polston et al. [630] studied the detection of text insertions or substitutions using magneto-optical measurements. They used new functions available on CADR software that allow to isolate letter or word from the total sensor area. In this way, magnetic inductions of letters or words can be measured to detect an insertion in the text of toner-printed documents. In this same context of investigating alterations to documents, Polston et al. [631] assessed the impact of hysteresis and other induction spatial effects on magnetic flux measurements of toners. Results confirmed that sensor orientation is an important factor that must be accounted for in method protocols for the measurement of magnetic flux of toners.

Another challenge in detecting altered toner-printed documents is to investigate if the document has passed through the printing process more than once. This study by Ma et al. [632] explored the influence of a second fusing on the microscopic morphology of toner, on 17 different models of laser printers from HP, Canon, Lenovo, FUJI, and Epson. The effects of fusing on micrographs of toner were first studied, then the differences of microscopic morphology between once- and twice-fused toner printed by the same laser printer were compared and analyzed through identifying significant correlations of average gray value.

Ma et al. [633] studied the operating regularities of the stepper motor inside inkjet printers to identify printing alterations made by the same thermal inkjet printer. They determined the periodic morphological characteristics of ink marks combined with the maximum gauges of the printers which could be used to judge how many times a document was printed.

Suzuki et al. [634] investigated photoacoustic (PA) imaging for the examination of altered documents by an innovative system with a nanosecond pulsed laser, a microphone, and a handmade sample holder. The PA signals from lines written by black pens on paper were successfully detected and the signal amplitude was found to depend on the type of writing pen. Alterations made by the addition of a line, or an obliteration were clearly observed by the PA imaging, showing this to be a high-potential technique to discriminate writing inks and to examine altered documents.

Because black gel inks are made with different types of pigments, it was hypothesized that their resistance values could be used to differentiate between different pen models from the same brand and among brands [635]. The author was able to use electric resistance measurements as a non-destructive, convenient, and effective method to identify documents written in black gel ink that contained alterations or additions. This is a to identify altered documents.

The article by Bhardwaj et al. focuses on the analysis of the reverse side of a questioned document, to show how pen ink intensity can potentially prove that a document has been altered [636].

Dansena et al. used Convolution Neural Network (CNN) to identify cases of alterations [637]. Since CNN requires a large amount of labeled data for training, the authors generated a large dataset for the experiments relating to handwritten word alteration detection. An approach for synthetic word data generation was presented in this paper for handwritten word alteration detection experiments.

Research also extends to alterations of digital documents [638]. Abd Warif et al. studied the detection of what they termed as ‘copy-move’ forgeries (CMF). Their detection methods relied on several fixed threshold values in the filtering process, and so their research proposes an efficient CMF detection method with an automatic threshold selection, named as CMF-iteMS.

As with previous sections, the three conference presentations included in this section are only provided as reference material [639–641].

#### 4.7.2. Charred and fluid-soaked

Although charred and fluid-soaked documents is a topic of study during training in FDE, there is not a wealth of information that has kept up with the advances in applicable technology. During the period under review there were no articles published, nor any presentations or workshops held to advance the understanding of techniques used in the stabilization and recovery of information from charred and fluid-soaked documents. This is a serious gap that will be discussed further in this article.

#### 4.7.3. Reconstruction

Under the umbrella of document reconstruction, three articles [642–644] were published dealing with fracture matching of the fragments or pieces of hand-torn or shredded documents. Another two conference presentations were given on the topic [645,646].

A general forensic study [642] conducted on various materials, documents included, was authored by Brooks et al. Their comprehensive review set a baseline for the current state of fracture matching, or physical fit, research, the limitations faced due to the unpredictable nature of casework, and the future directions of the discipline. The article also evaluated current practices through a review of standard operating procedures.

To put torn banknotes together, authors Yılmaz and Nabiyev proposed an automatic reconstruction system using reference banknote images [643]. First step of the reconstruction method consisted of matching fragments with the front and reverse faces of the reference banknote by using AKAZE method, followed by the detection of false-matched key points and alignment of fragments using RANSAC method. Correctly aligned fragments were assembled, and to recreate the banknote, the torn fragments of one side were flipped by creating a synthetic copy from the reference banknote images. The proposed method was used on 12 torn banknotes from a dataset and the average success rate was calculated as 95.55%.

A previously proposed method to facilitate the assembly of crosscut shredded paper documents by manual means was investigated [644]. Reassembling shredded plastic cards, such as debit, credit, or identity cards presents different challenges than paper documents but can also be less complex in several respects than reassembling shredded paper. This paper outlined a procedure to reassemble a small amount of crosscut shredded plastic cards in actual casework.

### 4.8. Digital documents

Over the past years FDEs have been increasingly tasked to examine documents for which the originals no longer exist, and the only copies available for examination are digital in nature. And while the FDE does not typically consider the same information as those in a digital and multimedia forensics team would, the FDE must respond to many of the same questions posed for hard-copy documents, such as is the document authentic, was it produced at the same time as another document, or has it been altered in any way? This section exists independently in this review because it is now the subject of study within the field of FDE as examiners are called upon more and more to examine digital documents. In the period under review nine articles [647–655], 13 conference presentations [656–668], and five workshops [669–673] were dedicated to this subject.

A text was published during the review period by Safonov et al. entitled Document Image Processing for Scanning and Printing [647]. This text presents a good overview of methods and software solutions for copying and scanning various types of documents by conventional office equipment, offering techniques for many common manipulations of digital document creation by scanning, including automated methods. This book provides the reader with a good basis of how most users will approach digital imaging of documents.

Lee et al. [648] extracted brightness variations from scanned digitized files to identify the scanner model. The color of digital image was separated into RGB and HIS, and then gradation and brightness adjustment were made. The best visible channel was selected to determine changes in brightness. They evaluated five scanner models and each ones had unique brightness variations.

Nandanwar et al. [649] presented a new expert system for detecting

forged and altered digital documents, specifically IMEI numbers and altered air ticket images. Experimental results on their dataset of forged IMEI numbers, on altered air tickets, on benchmark datasets of video caption (tampered) text, and on altered receipts of the ICPR 2018 FDC dataset, show that the proposed method was robust across different datasets. Furthermore, comparative studies of the proposed method with the existing methods on the same datasets show that the proposed method outperformed the existing methods.

Dixit [650] proposed a forgery detection technique in which Center Surround Extrema (CenSurE) detector is applied for key point detection from images. Experimental results show that the proposed technique could effectively detect forged images containing reflection and non-affine transformation with geometrical attacks, as well as robustness against erosion, dilation, RGB color addition, zoom motion blur, JPEG compression, spread noise addition, and multiple copy-move attacks.

Li et al. [651] proposed a method for the detection of double JPEG compression and its relation to counterfeiting and the detection of altered documents using a convolutional neural network (CNN). In this data-driven approach taking input from both raw JPEG DCT coefficients and decompressed image pixels, the authors explored CNN capabilities of learning deep representations from training data, thus effectively detecting double JPEG compression.

Many identification documents are first created in paper form, then immediately scanned, digitized, and further processed in electronic form [652]. Widely available photo editing software has made image manipulation simple and pervasive thereby increasing the risk of forgery. In this paper, the authors described an efficient recaptured digital document detection based on machine learning; the same machine learning that is behind some of the most successful content manipulation solutions can also be used as a counter measure to detect them. The core of the system was composed of a binary classification approach based on support vector machine (SVM), properly trained with authentic and recaptured digital passports. The detector informed when it encounters a digital document that is the result of photographic capture of another digital document displayed on an LCD monitor. Results showed that the performance of the detector remained above 90% accuracy for most cases.

The article by Slavin et al. [653] focused on methods to detect falsified business documents from scanned copies. The team proposed a method of comparison of two scanned images based on the recognition and analysis of N-grams word sequences. This was tested on a private dataset, demonstrating high quality and reliability of the search for differences in two samples of one agreement-type document.

In this study [654], Mondal et al. explored a Multi-Tasking learning (MTL) based network to perform document attribute classification They used a MTL based network for the classification of a full document image, based on segmented word images and patches. such as the font type, font size, font emphasis and scanning resolution classification of a document image. Subsequently, they proposed a MTL and MI (using segmented words and patches) based combined CNN architecture ("MTL + MI") for the classification of same document attributes. Then, based on the multi-tasking classifications of the words and/or patches, they proposed an intelligent voting system which is based on the posterior probabilities of each word and/or patch to perform a classification of document's attributes of a complete document image.

Hu et al. [655] proposed a new geometric correction method, different from existing methods, to correct deformation of digital images created by the many processes of physically placing hard-copy documents on scanners, or other digital input. Geometric deformation is usually complex and different from page to page; therefore, the quality of digital images can greatly affect any subsequent processing, e.g., document analysis and character recognition, geometric correction of document images is of great practical value. Both the visualized observational results and the statistical results proved that the proposed method could obtain a better correction performance and took less than half the time of the comparison methods.

As with other sections, only the articles are summarized here; the presentations and workshops from conferences are included in reference only [656–673].

#### 4.8.1. Security documents examination

There are FDE laboratories that uniquely consider the examination of security documents, for example, many immigration or border control laboratories, as well as laboratories in central banks. Security printing as an industry hosts many international conferences to share novel techniques and components in the production of security documents, and those FDE working in this domain would typically review these resources. Given the many advanced technologies in use in the field of security documents production it is not surprising that over the past years included in this review there have been many conference presentations of interest to those FDE who specialize in security documents examination, as well as two textbooks [674,675], and 24 published articles [676–699]. In fact, there were approximately 1200 conference presentations given on topics related to security documents examination over the period of this review, however only a selection was included in this article [700–840].

Two textbooks were reviewed that apply to this section on security documents examination: Rohrig, in his Chemistry of Money text [674] details advances in materials science and chemistry that have been applied to currency production. This text also includes information on counterfeiting and anti-counterfeiting measures over time. The second text, Coins and Currencies: An Historical Encyclopedia [675] provides a timeline of monetary history along with a glossary and bibliography which is relevant to the dating of paper currencies and those of other more modern substrates.

Talianchuk researched and proposed classification criteria of the types of inspection that identity documents are subjected to when used to cross the state border of Ukraine [676]. Inspection procedures were established to determine the type of passport document, examine its general appearance, verify its details, examine images, examine the pages, establish the validity of existing visas, and use appropriate technical equipment to detect signs of complete or partial forgery in passport documents. The peculiarities of studying these documents were also systematized and considered to identify signs of forgery.

The study by Mohamed et al. [677] set out to discriminate between counterfeit computer-generated one hundred Egyptian pound notes and genuine ones using non-destructive techniques. They applied the spectroscopic techniques of Fourier-Transform Infrared Spectroscopy (FTIR) as qualitative analysis combined with Scanning Electron Microscopy -Energy Dispersive X-Ray Spectroscopy (SEM-EDX) as quantitative analysis. They also used a video spectral comparison device as a physical technique. The result showed that the physical approach was superior for the classification and discrimination of color laser printing machines which encoded source serial numbers regardless of the toner type. The spectroscopic techniques were useful in discriminating the color laser printing machines which did not encode their serial number.

Pjanic et al. [678] published research presenting a layered printing method consisting of superposed visible CMY and invisible fluorescent ultraviolet (UV) RGB inks. This approach can be used to generate a variety of visual color-alteration effects such as revealing two completely distinct images when the print is illuminated with either standard visible or 365 nm ultraviolet (UV) light.

One article [679] described a system for identifying an anti-counterfeiting pattern based on statistical differences in specific image regions. One aspect of anti-counterfeiting detection is determination of the authenticity of security labels affixed to products: another class of documents. The authors exploit the randomness of ink diffusion in the printed anti-counterfeiting pattern which comprises subtle texture patterns. The algorithm system was able to successfully identify the patterns with high discrimination, however testing of arbitrary patterns and poor environments was not yet realized.

Muthamma et al. wrote a review on the use of carbon dots as emerging luminophores in security inks for anti-counterfeit applications [680]. Recent advancements reported on the security inks formulated from various carbon-based nanomaterials such as carbon nanodots, carbon quantum dots, graphene quantum dots and carbonized polymer dots for realizing advanced anti-counterfeiting were highlighted.

Guo et al. [681] proposed a method to prepare carbon dots that can be used for security printing. The authors used lycium ruthenicum as the carbon source, to prepare eco-friendly carbon dots via a one-step hydrothermal method. These carbon dots were incorporated into fluorescent inks and their anti-counterfeit effect on inkjet printed and handwritten documents examined. The authors expect these carbon dots to be an alternative material to be applied in the security field.

Liu et al. studied reversible thermochromic materials as good candidates for anti-counterfeiting printing. Their study investigated reversible thermochromic materials with good discoloration properties, which were used as fillers to prepare a new type of reversible thermochromic ink [682].

The team of Marques et al. [683] set out to create a non-destructive identification document inspection with swept-source optical coherence tomography (OCT) imaging. They analyzed identification documents using optical coherence tomography imaging and established the usefulness of this technology due to its sub-surface imaging capabilities for quantitative visualization of embedded security features in these documents, increasing the accuracy in forgery detection. However, this system is limited, by the small scan area and its price for an application in front-line. Previously, this team [684] published research wherein they applied OCT to the latest generation of polycarbonate travel documents having security features embedded within the polycarbonate layers. This sub-surface characterization by OCT of translucent structures non-destructively enables quantitative visualization of embedded security features.

Amjed et al. [685] presented an approach based on network science to detect document forgery using Laser Induced Breakdown Spectroscopy (LIBS) ink spectrum.

Bouma [686] proposed that new artificial intelligence-based technologies can assist in the automated fraud detection of travel and breeder documents, which may lead to more reliable and efficient border controls. Their paper presented five categories of new technologies in automated document authentication to overcome the limitations of current document analysis systems in automated and non-automated border control scenarios. The categories include the examination of visual security features from biodata pages, the analysis of breeder documents, and visa stamps, as well as other non-document related information, all combined to authenticate travelers' documents faster and more consistently.

Green wrote about the use of pantographs as a security feature [687]. This article explained that those security documents that contain a "void" pantograph as an anti-copying technology display weakness as scanning technology improves. The article details how a machine-generated copy of such a security document did not display the "void" warning, and that the successful reproduction of the document, lacking the "void" pantograph, was attributed to the higher scanning resolution of the photocopier used for the fabrication.

Another article [688] discussed public awareness of security features on bank cheques and the detection of counterfeits. Their study was conducted to identify the security features of different bank cheques, both original and scanned copies, using different methods including examination with UV light, transmitted light, and stereomicroscopy.

Johny et al. [689] researched novel security features for travel documents and other security applications; a dual waveguide based invisible fluorescence security feature with lifetime discrimination and a simple validation system. They embedded rare earth terbium (Tb) and dysprosium (Dy) doped fluorescence waveguides into identity documents as micro-threads or tags which are invisible to the naked eye and are only machine readable. Their proposed validation system consists of a modulated excitation source and fast photodiodes for the simultaneous detection of multiple security features from the fluorescence waveguides. The different emission wavelengths and lifetimes of these rare earth elements is a key differentiating feature, providing selectivity and security to the detector systems.

Fouad and Saif [690] investigated the synthesis, spectroscopic and photoluminescence properties of a novel nanophosphor complex for forensic applications, including the development of luminescent ink for anti-counterfeiting applications in the security printing industry.

Nogueiraa et al. [691] proposed a manual method for the deposition of photoluminescent inks based on mixed lanthanide organic frameworks applied to document encoding. The resultant optical properties of their synthesized LOF material were tested using photoluminescence spectroscopy, resulting in good spectral and mechanical stability. This ink demonstrated potential to function as a low-cost alternative for other photoluminescent inks on security documents.

Another group published a comprehensive review of luminophoric organic molecules for security printing applications [692]. This review introduced various techniques to combat the growing threat of counterfeiting and explains the different types of luminophores currently used in anti forging applications. The article mainly highlighted recent developments in organic solvent-based and eco-friendly water-based formulations for anticounterfeiting purposes, including the limitations of the currently used organic materials and future prospects for fabricating smart luminogens to tackle counterfeiting problems.

The team of Tkachenko et al. [693] explored pharmaceutical packaging printed on blister foils using rotogravure process for counterfeit identification purposes. They showed that the chemical etching has a stochastic nature that can be spotted by correlation or classical machine learning methods, and therefore proposed an authentication system using a novel regular test pattern of blister foils. Both the cylinder used for printing and the position of the regular test pattern engraved on the authentic cylinder could be identified; fake patterns printed using counterfeiter cylinder and rotogravure press could also be rejected. The authors planned to expand their proposed system to other types of engraving processes.

Beginning in earnest during the COVID-19 pandemic was the necessity to examine images of identity documents for genuineness or evidence of alteration. The paper by Al-Ghadi et al. [694] proposed a reference hashing approach (i.e., CheckScan) to discriminate between the original template of the identity document image and a scanned one. Their discrimination process was conducted between two aligned identity document images in two steps: feature extraction based on Fast Fourier Transform (FFT) and hash construction. Using the Mobile Identity Document Video dataset (MIDV-2020) for their experimentation, their results showed that the proposed approach builds binary codes quite discriminative for distinct identity document images.

For forensic document examiners who focus on currency examinations there were several interesting articles included in this review.

Bicchieri et al. [695] worked to determine if non-invasive scanning macro-X-ray micro-fluorescence (MA-XRF) imaging combined with μ-RAMAN spectroscopy could discriminate between historical and modern materials used for paper currency in China. This research allowed the authors to then identify seven out of nine counterfeit pieces of Chinese currency.

Baek et al. [696] proposed a banknote ageing simulator for generating aged and soiled banknotes from new ones.

Novais Rodrigues et al. [697] analyze banknotes by portable XRF and portable Raman (785 nm) and discriminate them according to the authenticity. As the Raman and XRF are portable, the size of the analyzed area is important, so the reproducibility of the measurements could be discussed. The printed techniques used in the counterfeit banknotes is not presented and a simple optical analysis could discriminate them from the genuine ones.

Lee et al. [698] proposed a method to identify the colour printers used to print counterfeit banknotes based on analysis of their halftone

textures. The non-destructive technique uses a classification algorithm and CNN and was found to be highly accessible and efficient as it can be performed using any scanner.

Vittorazzia et al. [699] published a new method to identify the authenticity of Brazilian banknotes using digital image analysis by the smartphone application Photometrix® which is associated with chemometric tools. The team conducted experimental planning to determine the best regions for analysis along with pixel region size and variations of smartphone devices, with promising results obtained. The application promises potential for analyzing the authenticity of banknotes by digital images making it a fast, non-destructive, portable, and low-cost approach that is accessible across society.

As previously mentioned, only a selection of the many conference presentations is listed in the references of this article. For ease of reference, the presentations have been organized by topic. There are 19 presentations [700–718] that generally cover security documents' examination. Another 11 refer to security printing [719–729], while three have as their subject substrates [730–732]. There are 40 presentations in reference covering security features [733–772], 18 about identification documents (ID) examination [773–790], one presentation concerning art [791], 15 about travel documents [792–806] and a further 23 [807–829] concerning aspects of currency (i.e., banknotes). There are 11 workshops [830–840] covering various topics concerning security documents' examination included in this article.

## 5. Forensic intelligence

Forensic intelligence is not a new concept and has been studied and applied in the security and intelligence community for decades already. However, this term is gaining in academic popularity and being employed successfully in certain progressive laboratories over the past few years. Despite this popularity, only one article and three oral presentations about forensic intelligence also included forensic document examination as a subject of study. By far most of the study in forensic intelligence is holistic in nature, however it is expected to flourish as a topic of interest in the field of FDE in the near future as the applications for success become more widely known.

The article by Zanina et al. [841] encapsulated a study of the theoretical and practical aspects of counterfeit and adulterated products using a comprehensive research approach, which in essence is the use of forensic intelligence. While this topic includes many other fields, documentary examination is key as documents such as product instructions, accompanying documents, warranty cards, certificates all require appropriate forensic document examination. The result of a comprehensive study provides not only the solution of the question of originality of products, but also how the products were falsified. The authors conclude that examining counterfeit products entails the most complex of examinations and requires a comprehensive approach involving many specialists in various fields of knowledge, with extensive experience, availability of information and technical support.

The three conference presentations that dealt with forensic intelligence and its use of, or application to forensic document examination are included in Refs. [842–844].

## 6. Quality Assurance

Assuring quality in forensic document examination as with the other disciplines, has been the subject of serious study within the past 20 years with publication of reports such as the US National Academies of Science report (2009), and the follow-on President's Council of Advisors on Science and Technology (2016). Worldwide there has been recognition that the forensic sciences require attention. Although there is a separate article within this 20th IIFSMS Review, that considers quality management, within FDE there are advances and updates to be made that are domain specific and so are included here.

### 6.1. Human Factors and Cognitive Bias

A seminal work examining the role of human factors on handwriting comparisons was completed in 2020. The Report of the Expert Working Group for Human Factors in Handwriting Examination published the report Forensic Handwriting Examination and Human Factors: Improving the Practice through a Systems Approach [845]. A further nine articles [846–854], and 24 conference presentations [855–878], including one workshop on decision-making and cognitive bias in FHE signature comparisons, comprise this section, most of which spawned from the HFHE study.

The importance placed on this discipline by the NIST/NIJ in gathering experts from various fields related to questioned documents to discuss the human factors that have effects on handwriting examination is encouraging. This highlights that questioned documents, as a forensic science discipline, is not performed in a fundamentally different manner, nor should it be, in other parts of our world. Internationally recognized protocols and best practices are extremely important because forensic science, its practice, and its use, is interjurisdictional and multidisciplinary in nature.

Further to the work of the NIST expert working group on human factors, Osborne et al. [846] provided recommendations relating to cognitive bias and contextual information management in handwriting examinations.

Dror et al. [847] studied the biasability and reliability of the judgments of 25 expert forensic document examiners who did not know they were being tested. Findings from this study, wherein half the experts were informed they were working for the prosecution and half for the defense, show that experts' decisions were not affected by this knowledge. However, there was a lack of reliability in the decision-making highlighted by the lack of consistency in conclusions among the examiners.

Ommen et al. [848] set out to establish the scientific validity of expert writership opinions and the two-stage approach to evidence interpretation using measures derived from research on handwriting motor control. This comprehensive study involved 33 subjects writing six phrases using an inking pen on paper placed atop a digitizing tablet to record x, y, and z data at a capture rate of 100 measurements/second. Their findings supported the experimental questions.

Kang et al. studied the factors that affect error rates in handwriting examinations of Korean characters by forensic document examiners and non-experts [849]. Their study resembled previous studies with different scripts conducted to determine validity of FHE with respect to experts versus laypersons, although it used a relatively small pool of both forensic handwriting examiners (four) and laypersons (20). Their findings also mirror previous studies in that incorrect responses were much higher in the layperson group while inconclusive opinions were higher in the expert group, and that adding in a peer review step reduced error rates.

Ribiero et al. [850] presented an interesting study on beliefs about error rates and human judgement in forensic science. Their findings suggest that people believed that the process of forensic science involved considerable human judgement and was relatively error-prone, and that for certain forensic techniques such as forensic document examination, study participants were more skeptical of certain forensic evidence than they needed to be.

Varshney and Bedi wrote of the Lacunae in Forensic Handwriting Examination: Scope for Exploitation [851]. Their article presented the process of handwriting analysis and explained how bias could arise in the subjective part of the examination and evaluation of observations. The article goes on to discuss ways to limit this bias.

Carvalho de Melo et al. analyzed the main criteria most often reported by experts in the analysis of signatures and found that the criteria of initial and final pen strokes and handwriting progress were not statistically relevant indicating that subjectivity is essential for the experts to make correct analyses [852].

Merlino et al. have also been conducting research on cognitive factors in handwriting examination, publishing two articles on the topic in the Journal of the American Society of Questioned Document Examiners [853,854]. Both articles report on initial findings from an interdisciplinary study to explore the reliability, measurement validity, and accuracy of established FDE methods and procedure, and to also investigate the influence of possible sources of cognitive bias in the methods and procedures of forensic handwriting examination. The study employed eye-tracking experiments in which the characteristics of signatures, characteristics of the visual context, and the gaze behaviour of the participants are combined to investigate how these factors relate to examiner decision accuracy. This research aims to build from the recommendations of the NIST Expert Working Group for Human Factors in Handwriting Examination report to conduct multidisciplinary research efforts to study neurological, physiological, cognitive, social, and environmental factors that form the context in which handwriting examination takes place.

The 24 conference presentations and workshop that dealt with the topic of human factor and bias in FDE are included in reference only [855–878].

### 6.2. Validity and the courts

In response to the questions posed by many of the critiques of forensic science concerning validity and the courts, there has been an increase in the study of reliability and validity of forensic science FHE/FDE evidence and the traditional systems of expressing opinions and measuring decisions. To this end there were nine articles [879–887] included in this review, as well as 37 conference presentations [888–924], and five workshops [925–929] dedicated to exploring FDE/FHE interactions in the courtroom.

Li and Li [879] wrote a review of handwriting expertise reliability in an effort to strengthen the reliability of handwriting identification in China.

In Poland another study was undertaken [880] to create a new system of experts in handwriting examination for law enforcement and the judiciary; Polish courts have an expert registry. Problems encountered in this analysis included the opinion scales in use as well as the lack of a reliable and comprehensive training system for experts, leading the author to deduce that the work to replace the current system was long and difficult.

Saha and Jena in India [881] proposed a quantitative study in FHE to measure decisions of handwriting examiners to illustrate the science involved in the examination of handwriting and the expression of opinions.

Chin and Ibaviosa [882] wrote about how FDE ranks in terms of public perception of the credibility of forensic science in their 2022 article "Beyond CSI: Calibrating public beliefs about the reliability of forensic sciences through openness and transparency." The article reviews several studies as well as empirically tested ways other fields are addressing this same issue, resulting in recommendations to improve credibility.

In 2019, Ostrum [883] prepared what is now considered a foundational thought piece regarding the use of the logical approach to evidence evaluation. His article set out the position of the Canadian Society of Forensic Science' Questioned Document Section that the logical approach to evidence evaluation and reporting is an appropriate and effective option for forensic document examination work when implemented as outlined in the paper.

A 2021 paper evaluated the accuracy and reproducibility of forensic handwriting examiners' decisions [884]. This paper provides value to the study of likelihood ratios in forensic handwriting examination although somewhat rudimentary.

Tanaka [885] chronicled an increasing role for the FHE/FDE in his paper describing the work of Justice Rapid Response and the relevance of questioned documents examination to war crimes and crimes against humanity prosecutions at various international tribunals, the International Criminal Court, and the Extraordinary African Chambers.

In an historical review, Durina [886] revisited the famous Lindbergh kidnapping case to provide an interesting and educational retrospective for modern experts. Another publication of previously un-published historical information came in 2021 as JASQDE published a 1931 manuscript entitled Special Topics in Disputed Document Testimony [887]. Publication of early works provides important insight to the role of FDE/FHE in courts from early days and serves to dispel myths that this discipline is novel.

As with previous sections, conference presentations [888–924] and workshops [925–929] are included only in references.

### 6.3. Standards and best practices

While there were many articles published during the period covered by this review that concern standards and best practices in the forensic sciences, most were holistic in nature and did not solely concern FHE/FDE and so are not covered by this review.

Although this topic was much more prevalent as presentation or workshop material at conferences in that there were 37 presentations and six workshops programmed at international meetings, two textbooks were published during the review period that update forensic document examination as a whole. Kelly and Angel [930] compiled Forensic Document Examination in the 21st Century – a text that covers the latest technology and techniques providing a complete resource on contemporary issues and methods in forensic document examination. This is an up-to-date reference that includes technological advances, such as electronically captured signatures and computer-generated documents, as well as traditional subjects within FDE.

Asdal and Reinertsen, in their text, present a framework for studying documents to conduct a rich and systematic analysis of documents in all their diversity [931]. Focusing on practical document analysis the book provides an innovative and versatile toolkit for analyzing print and digital documents, highlighting the impacts of digitalization on documents themselves and the methods used to study them.

In their article, Cadola et al. [932] conducted research to pilot a novel approach to teaching handwriting examination to university students through five activities whereby the students created their own learning materials. In this approach, students took the roles of victims, forgers, teachers, and experts to become aware of the possibilities and limitations of signature comparison. Through this collaborative learning, students' theoretical knowledge was improved while making them aware of the limitations to their practical skills.

In their 2021 paper, the team of Ivanovic et al. [933] conducted an in-depth focus on existing approaches, systematizing theoretical knowledge, studying, and analyzing forensic expert practice in the provision of scientifically substantiated, objective, complete forensic reports and all its types, with a goal of reducing erroneous expert conclusions.

As noted previously, there were 37 conference presentations [934–970] and six workshops [971–976] dedicated to this topic of standards and best practices in FDE that are not described here but are rather included in references only.

## 7. Miscellaneous

Despite the many different category titles included in this review article, there are still some articles that do not adhere to any. Although a small section, this miscellaneous grouping comprises only two articles but many more conference presentations spanning topics such as new technologies through hidden messages, to the availability of resources and talent management.

Chen et al. [977] investigated the effects of long-term Chinese calligraphic handwriting training on anxiety and attention, as well as brain structure. Although this research was undertaken for neurological

testing, it is important for the FDE to note that the results also showed that there were no significant differences found in the handwriting-related regions of interest in the brain structures between the control group evaluated and the group having at least five-years of CCH training. And although not the focus of this research it is worth noting that this supports the theory that once handwriting is developed as a mature habitual motor skill, it is relatively stable, and that calligraphy is a separate form of handwriting.

Wilkinson et al. [978] conducted a study of the effects of decontamination agents following biological contamination on fingermarks, documents, and DNA. This study assessed, among other types of evidence, documents comprising handwritten samples made with ten different inks and pencil, and printed text from both inkjet and toner technology to determine the effects of decontamination agents on physical evidence contaminated with Bacillus thuringiensis, an anthrax surrogate. The results noted that decontamination agents would not negatively affect stereo microscopic examination nor latent indentation examinations of these documents.

The 26 conference presentations that deal with the diverse miscellaneous topics related to FDE are included in reference only [979–1004].

## 8. Trends, challenges, and gaps

The field of forensic document examination has been an autonomous forensic science since the late 1800s, and since this time there have been innumerable changes that comprise the evolution of the science. Since the previous IIFSMS Review in 2019 the main focus of FDE has been on the expression of forensic opinions and conclusions. That said, this discipline does look to many other fields for scientific advancements that can be applied to casework.

With respect to trends in the field, there has been an increase in awareness between the document analysis and recognition fields and FDE in the application of automated handwriting recognition methods. This carries over to the other aspects of FDE in the assessment of digital documents and the need to work collaboratively with both the digital forensics fields and the wider fields of computer document analysis and recognition. Moreover, we can see that the use of artificial intelligence in document authentication is burgeoning, and its time has come, spurred on by global needs as a result of the pandemic. Innovation in this direction will have direct application to FDE and for the examiners working in the field. As a final point, the use of chemometrics applied to analytical techniques has increased sensitivities of methods, allowing for more, and more precise conclusions, as applied across all fields, including FDE. This trend is expected to continue.

By way of example, the following four articles highlight some novel work in questioned documents.

Brain Computer Interface (BCI) is the technology used to assist those suffering from spinal cord injuries to interact. The research by Willett et al. involved the use BCI to assist paralyzed patients to execute the writing act using neuronal activity signals. This technology and these studies on handwriting production, although novel, represent a field of further study for the FDE to determine if the handwriting of an individual prior to paralysis and that of the same individual using BCI can be compared. Another avenue of research to further explore is comparison of the handwriting produced by someone not paralyzed alongside the same person's handwriting produced using BCI. A study of this sort would add to the body of knowledge concerning individuality in handwriting as well as persistence of handwriting skill and habits [1005].

Following on from this study of BCI is one that concerns the synthesis of handwriting. Handwriting synthesis generates renderings of text which resembles natural writing but are synthesized from actual handwriting samples. Their article investigated sample acquisition for handwriting synthesis, in particular studying how much input variability was required to represent specific handwriting [1006].

The explosion of wearable devices and their applications has given rise to another novel application that must be further studied by the FDE community. In this article the authors [1007] explore the feasibility that wearable devices can be used as a practical, user-friendly, inexpensive, and reasonably accurate way to authenticate handwriting. This research included imposter attacks, simulation using model handwriting and additionally having access to video showing the writer's handwriting production. Interestingly, this application sees the authentication of handwriting, instead of signatures.

A final paper was found to potentially reverse the question document workflow and start with DNA collection for those cases that are submitted for handwriting comparison or latent indentation examinations. McLaughlin et al., [1008] established a dry vacuum method for DNA evidence collection from the entire surface of a document. This paper is of importance to workflow planning within the forensic laboratory, however as the technique only tested for certain questioned documents cases, e.g., latent indentation examinations, it may not be suitable to employ widely.

There are six conference presentations that are included in reference for this section [1009-1014], with topics ranging from the digital/-physical transition and "phygital IDs" to trend analyses of specific regions.

One significant gap identified during this review is the abject lack of new or updated research on the preservation and examination of charred or fluid-soaked documents, despite that there are few resources that deal with this topic and little research, or literature published in the discipline in general to aid the FDE in treating and handling these document circumstances, or in recovering the information from these documents. No doubt many laboratories have methods in place for these cases, however the lack of available literature and techniques is seen as a gap in the discipline that should be mitigated by renewed study and application of these techniques and perhaps development of new ones.

A major challenge in the field of FDE is that the number of qualified examiners is shrinking in many regions. This field is relatively small, and training to competency is long compared to other fields of study. Compounding this is that as with other fields of forensics, expertise includes an experiential quality that necessitates time to develop. These aspects, combined with the focus of crime laboratories towards the resolution of crimes of violence means that forensic document examination units are becoming less desirable in the public sector given various stressors within the laboratory ecosystem. In many parts of the world there has been a trend towards the offload of public work in FDE to a small private sector. The long-term result of this trend may be the disparity in the availability of this evidence, the use thereof being determined by the ability to afford this expertise.

Despite this lack of qualified personnel, there is no shortage of work in the field, as can be evidenced by the steady increase in fraud on a global scale [930], including elections fraud, immigration fraud and tax/fiscal fraud, for example. Moreover, corruption, identity crimes, and other financial and economic crimes are viewed by major international organizations as enabling crimes that rob wealth and support organized crime activities such as human trafficking and migrant smuggling, contraband smuggling, and money laundering [1015]. These are the crimes that tend to require forensic document examination for their resolution.

These challenges are noted by the many professional organizations that comprise forensic document examination, and work continues to address them. Meetings of international organizations, such as this INTERPOL IFSMS are venues in which these topics and the challenges faced by the field may be discussed in light of the advances in the technical aspects of the discipline.

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