



FORENSIC ANALYSIS OF ACID AFFECTED TEXTILE FIBRES USING SPECTROSCOPIC TECHNIQUES: A REVIEW

Uzma Mushtaq*, Ansil P. Naseef, Nithin Kumar Reddy

India.



***Corresponding Author: Uzma Mushtaq**

India.

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ABSTRACT

Corrosive substances are often involved in acid-attacks, industrial accidents, evidence destruction, and chemical assaults. The effect of strong mineral acids like sulphuric, hydrochloric, and nitric acids on various materials may be determined by characteristic alterations such as textile fiber degradation, paper yellowing, wood carbonization, polymer chain cracking, rubber decarboxylation, and skin protein denaturation.^[8–10] Modern analytical techniques such as Fourier transform infrared spectrometry (FTIR), attenuated total reflectance Fourier transform infrared spectrometry (ATR-FTIR), scanning electron microscopy (SEM), Raman spectroscopy, gas chromatography-mass spectrometry (GC-MS), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and chemometrics have been utilized to investigate the nature of corrosive injury.^[1,3–7,11–14] The present review focuses on the effect of selected corrosive substances on various materials with an emphasis on textile fibers and the analytical techniques applied for their forensic analysis. The survey revealed that natural protein fibers undergo hydrolysis, dehydration, carbonization, and structural damage while most synthetic fibers experience melting, shrinking, and surface defect formation when exposed to the influence of strong acids.^[8,9,14] The current study also identified the necessity of additional methodological and database developments for the reliable identification of corrosive substances in a forensic setting.^[2,10,13,14]

KEYWORDS: Corrosive substances; Forensic examination; Acid attacks; Textile damage; FTIR; ATR-FTIR; Scanning Electron Microscopy; Chemometrics; Crime scene reconstruction; Forensic chemistry.

1. INTRODUCTION

Corrosive substances are among the most destructive chemicals encountered in forensic science because of their ability to cause irreversible damage to a wide range of materials. They are commonly associated with acid attacks, homicide, destruction of evidence, vandalism, malicious damage to property, and accidental industrial incidents.^[9,10] Owing to their widespread domestic and industrial use, strong mineral acids are easily accessible and frequently involved in both accidental and criminal cases. Their interaction with different substrates produces characteristic physical, chemical, and microscopic changes that often persist after the incident, providing valuable forensic evidence.^[8–10]

Sulphuric acid, hydrochloric acid, and nitric acid are the most commonly encountered corrosives in forensic casework due to their high reactivity and availability.^[8–10]

Sulphuric acid causes dehydration, carbonization, and embrittlement of cellulose materials, hydrochloric acid mainly induces hydrolytic degradation of fibres, while nitric acid produces oxidation, yellow discoloration, and loss of tensile strength. The extent of damage depends on the corrosive type, concentration, exposure duration, environmental conditions, and the properties of the affected substrate.^[8,9,14]

Textiles are among the most important forms of evidence in corrosive assault cases because they retain characteristic damage patterns and chemical residues even after washing.^[8,9] Natural fibres typically undergo dehydration, hydrolysis, carbonization, fragmentation, and loss of tensile strength, whereas synthetic fibres such as polyester and nylon exhibit melting, shrinkage, softening, and surface deformation. Blended fabrics display combined degradation patterns due to the different

responses of their constituent fibres.^[5,8,9] Corrosive substances also affect paper, wood, rubber, plastics, painted surfaces, and biological tissues, producing distinctive alterations that aid forensic identification. In biological tissues, strong acids cause coagulative necrosis, severe burns, and dehydration, providing valuable medico-legal evidence.^[9,10]

Advances in analytical techniques have significantly improved forensic corrosive examination. While visual inspection and light microscopy remain useful for preliminary assessment, modern laboratories increasingly employ FTIR, ATR-FTIR, SEM, Raman spectroscopy, GC-MS, XRD, XPS, and chemometric analysis for accurate characterization of corrosive-induced damage.^[1,4-7,11-14] FTIR and ATR-FTIR enable rapid, non-destructive chemical identification, whereas SEM provides detailed morphological examination. Complementary techniques such as Raman spectroscopy, GC-MS, XRD, and XPS further enhance forensic interpretation.^[1,3-7,11-14]

Recent studies have demonstrated that combining FTIR with Principal Component Analysis (PCA) improves the differentiation of inorganic acids on textile materials, while portable FTIR and Raman instruments enable rapid on-site analysis.^[11-14] However, challenges remain due to the lack of standardized analytical protocols, comprehensive reference databases, and studies involving mixed corrosives, diverse substrates, and realistic environmental conditions.^[2,14] This review therefore examines the forensic significance of sulphuric, hydrochloric, and nitric acids, their characteristic damage patterns, the analytical techniques used for their identification, and the current research gaps and future prospects in forensic corrosive investigations.^[2,10,13,14]

2. FORENSIC SIGNIFICANCE OF CORROSIVE SUBSTANCES

Corrosive substances play an increasingly important role in forensic examinations due to their frequent use in violent crimes, cases of chemical exposure, industrial accidents, and deliberate destruction of material objects. Among the various groups of aggressive chemicals, mineral acids are most common. This is explained by the relative availability of sulphuric, hydrochloric, and nitric acids and their wide use in economic activity.^[8-10] At the same time, the action of these substances on the surface of a material is often noticeable and helps predict their further action and determines their forensic significance.

2.1 Forensic Importance of Materials Damaged by Acids

Attacks with concentrated mineral acids are known as vitriolage. It is typically used to cause the victim to suffer the most severe physical pain, permanent injuries, and even disfigurement. In addition to the personal effects of the victim, clothes, shoes, and furniture in the room can be damaged, which can be of great forensic interest.^[9,10] This allows the investigator to reconstruct the entire event and determine the very substance of the

attack. Even more important is the study of the action of acids on various materials since their action is usually localized and leaves characteristic signs that can indicate both the type of substance and the direction of its action.^[8]

The action of aggressive reagents on various materials is a valuable source of information for forensic experts. The changes caused by acids are usually extensive and can be used to determine the location and direction of the attack, the duration of the action of the substance, and even the distance between the victim and the attacker.^[8-10] The appearance and nature of the damage depend on the type of acid, the physical state of the material, and the time of action. Even after washing and drying, damaged materials often retain signs that can help determine the corrosive substance. Therefore, the study of the action of acids on various materials is of great forensic interest since it allows the expert to obtain information about the conditions and course of the destruction. Textiles, paper, plastics, rubber, wood, metals, varnishes, and paint are some of the common materials whose damage is actively studied.

Sulphuric acid causes the most damage to materials due to its dehydrating effect. Due to the rapid removal of water from the surface, cellulose products become carbonized and brittle. Hydrochloric acid also has a damaging effect, but the main direction of its action is the hydrolysis of natural polymers contained in various fabrics. Nitric acid, in turn, is a strong oxidizing agent that destroys many materials through oxidation-reduction reactions and causes noticeable yellow stains.^[8,9] However, the action of each of these three common acids is unique in terms of the appearance of damage and changes to the properties of materials. This is especially important for the expert assessment of the destruction since the analysis of the front of destruction allows the forensic technician to differentiate aggressive substances with sufficient precision.

The action of acids on various materials depends not only on their concentration and properties but also on the physical and chemical composition of the substance itself. In addition to the chemical composition of the material, temperature, lighting, and the presence of other substances in contact with the acid affect the damage. Typical for natural materials is greater damage compared to synthetic ones due to the differences in structure.^[14] The variability of the action of a corrosive substance is of great forensic significance since it allows the expert to answer the question of which materials were subject to destruction and which were not.

The study of the action of acids extends beyond the framework of the criminal case itself. Examination of the effects of aggressive substances is a significant area of forensic activity and is of interest not only to criminalistics but also to other sectors of the economy. Such examinations are needed to establish the fact of

destruction, determine the substances that caused it, find out the conditions of destruction, and reconstruct the event.^[10] At the same time, the relevance of this area is not only due to the study of criminal incidents. The study of the effects of corrosive substances is also of great importance in industrial accidents, ecological problems, insurance cases, and even for examining the destruction of objects in cases of legal disputes.^[10] The expert assessment of the material damage allows the forensic technician to establish not only the nature of the aggression but also the way of destruction, and the location from which it began. In addition, for medical-legal expertise, the study of the damage caused to the skin allows the reconstruction of the injury using the characteristics of the destruction of the victim's clothing.

The latest achievements in technology and chemistry have opened up new opportunities to study the action of acids on all kinds of materials. In particular, researchers are now able to analyze characteristic changes in the chemical composition of substances using spectral, microscopic, and chemometric methods that are not visible to the naked eye.^[1,4-7,11-14] Thus, the study of the action of corrosive substances on various materials has become even more relevant and is actively used not only in the study of crimes^[1,7] and criminal cases in general^[6,9,10] but also in the solution of various scientific and technical tasks.

2.2 Interaction of Corrosive Substances with Different Substrates

The interaction of corrosive substances with various substrates is determined by the physicochemical properties of these chemicals. Strong mineral acids damage substrates through several processes, the nature of which is determined by the concentration of the corrosive substance, the duration of the action, environmental conditions, and the physicochemical properties of the substrate. These differences in the influence of acids on various substrates are significant for the forensic expert assessment of this type of damage.^[8-10,14]

A forensic examination of the action of strong mineral acids is most often carried out on textile materials, since these substances are most often found on the clothes of the victim. Textile materials are most often found as trace evidence in the context of acid crimes.^[8,9] The nature of the interaction of these materials with acids is determined by their composition, which makes it possible to identify the fiber composition and the degree of damage to the fibers. Natural fibers include wool and cotton, and their interaction with strong mineral acids is associated with their hydrolysis, dehydration, carbonization, fragmentation, and mechanical destruction. The destructive effect of sulfuric acid on cotton is the most spectacular among the action of all three acids due to the dehydrating properties of this acid, leading to the fact that cotton rapidly turns into carbon.^[8,9,14] The action of hydrochloric acid leads to the hydrolysis of cotton,

resulting in the destruction of cellulose and a decrease in the strength of this fiber. Nitric acid acts on cotton, destroying it through oxidation processes, resulting in yellow spots on the surface of the fabric.^[8,9,14] Wool fiber, which contains keratin, is characterized by a similar nature of destruction when exposed to concentrated sulfuric, hydrochloric, and nitric acid, but the process of destruction is different due to the structure of this fiber. Destruction of wool fiber also occurs with the formation of yellow spot, but this process is slower than destruction of cellulose.^[8,14]

Synthetic fibers differ from natural ones in the nature of the action of concentrated sulfuric, hydrochloric, and nitric acids. The impact of these substances on synthetic fibers is much less destructive, but over a certain period of exposure, they lead to the destruction of such materials. Thus, polyester and nylon do not dissolve when exposed to concentrated sulfuric, hydrochloric, and nitric acids, but their structure changes, leading to shrinkage and softening and changes in shape.^[5,8] The relative resistance of synthetic fibers to the action of concentrated acids allows for their long-term storage, which is another advantage in the forensic examination of this type of damage. Fibers made of synthetic and natural materials often have a mixed composition, and interactions of this type can be regarded as a combination of the action of acids on natural and synthetic fibers. Therefore, when examining mixed fibers, the ability to identify both the component composition of the material and the nature of the action of acids on their various components becomes a valuable source of information.^[8]

Although the action of acids on textile materials is of the greatest interest, this type of damage is not limited to fibers. Many other substrates also have characteristic changes under the influence of corrosive substances, among which the most common are paper, wood, rubber, plastic, concrete, and animal tissue. Paper and cardboard are most often damaged as a result of the destructive action of hydrolysis.^[10] The interaction of acids with wood is manifested in the destruction and carbonization of this material, while paper, cardboard, and plastic are brittle. Rubber is affected by acids through swelling, softening, cracking, and loss of elasticity.^[10] The effects of concrete and paint are manifested in their structural changes, which can be used as characteristic features of the action of various corrosive substances.^[10]

Biological tissues are also of particular interest of this research as the impact of concentrated mineral acids on them is extremely destructive. As a rule, the action of these substances leads to coagulation necrosis of tissues, burns, severe dehydration, and destruction of the structure of animal tissues. The nature of the damage depends on the concentration of the substance and the time of exposure, as well as the location of the burned area. A study of the nature of the injury to the victim's body together with an analysis of changes to his clothing can provide a forensic expert with valuable information

about the mechanism of injury.^[9,10]

The results of the research cited also note that the action of acids on various substrates often leaves behind signs of damage even after washing or other interactions of this type. Therefore, even when the traces of the corrosive substance itself are not available for examination, the nature of the destruction observed on the surface of the substrate can act as valuable evidence. This feature is especially important in forensic practice, since the presence of traces of corrosive substances can be inhibited by the passage of time after the crime.^[8,9]

Thus, all the described research results confirm the importance of studying the action of concentrated mineral acids on various substrates. The differences in the action of these substances on natural and synthetic fibers, as well as other materials, open up the possibility of using these differences in forensic practice.

For example, knowledge of these differences will allow a forensic expert to identify the nature of the destruction of various substrates, which will help analyze the conditions of the crime and the manner of the victim's death.

2.3 Analytical Techniques for Forensic Examination of Corrosive Damage

The analysis of substances involved in corrosive damage has seen significant developments due to the introduction of advanced techniques that enable the identification of chemical, structural, and morphological changes to the affected materials. The early studies relied primarily on visual inspection and light microscopy to document discolouration, fibre damage, and other visible effects of corrosion. Although these methods remain relevant and informative, their application is limited by the inability to provide detailed information about chemical interactions and structural integrity, particularly for similar classes of corrosive substances.^[1,4,9] Therefore, the current research makes use of alternative approaches that improve the accuracy and reliability of forensic identification.

Notably, Fourier transform infrared (FTIR) spectroscopy has become a powerful technique for forensic analyses since it allows for the rapid and non-destructive identification of the affected compounds with minimal sample preparation.^[1,3,22,23] This method has been extensively applied to examine the damage to cellulose, protein, and polymer structures by corrosive agents. More specifically, the alterations in the characteristic infrared absorption bands can be used to infer the nature of the chemical interactions, which include hydrolysis, oxidation, and dehydration processes.^[3,6,7] Additionally, FTIR spectroscopy has been widely implemented due to its speed and accuracy, making it a standard method in many forensic laboratories. Among the numerous variations of infrared spectroscopy, Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy has been recently recognized as a valuable

technique for forensic assessments.^[11,12] This approach can be employed to examine the chemical alterations of various types of solid materials without significant sample preparation. ATR-FTIR requires only a minute sample amount and is relatively non-destructive, which benefits forensic analyses in terms of preserving the integrity of trace evidence. Consequently, recent studies demonstrate the applicability of this variation of infrared spectroscopy to identify chemical residues and examine the degradation of materials subjected to corrosive damage.^[11,12]

In addition to spectroscopy, scanning electron microscopy (SEM) is a powerful tool for investigating the effects of corrosive damage. SEM has been extensively applied to study the structural changes to textile fibres exposed to various aggressive environments.^[4,6,25] The microscopic examination of the fibres revealed the presence of swelling, cracking, erosion, fragmentation, melting, and surface collapse.^[4,6,9] SEM imaging is particularly beneficial for forensic analyses since it provides a greater magnification and resolution compared to conventional light microscopy, thereby revealing intricate details of the damage.^[4,6,25] Overall, such information can be combined to create a comprehensive assessment of the effects of corrosive exposure.

Other analytical techniques that have been applied to forensic examinations of corrosive damage include Raman spectroscopy, gas chromatography-mass spectrometry (GC-MS), and X-ray diffraction (XRD), among others. Raman spectroscopy is particularly advantageous for determining the molecular composition of the sample based on its unique vibrational frequencies. This method generally requires minimal sample preparation and is applicable to a range of coloured and transparent materials.^[13] Meanwhile, GC-MS is a powerful technique that enables the identification of volatile and semi-volatile chemicals present in the sample.^[5,26,27] Notably, GC-MS has been used to detect chemical traces related to corrosive damage. On the other hand, XRD is primarily used to examine the crystal structure of materials, which provides insights into the nature of chemical interactions.^[4,6,7] The variation in the crystallinity of cellulose after exposure to different corrosive agents has been examined with XRD, while X-ray Photoelectron Spectroscopy (XPS) has been used to determine the chemical bonds and, therefore, the nature of the interactions.^[4,6,7]

With the development of chemometric software, the field of forensic analysis of corrosive damage is entering a new era of comprehensive and accurate examinations. More specifically, statistical analysis of spectral data has been applied to better understand the differences in the characteristics of samples exposed to diverse environments. Principal Component Analysis (PCA) is a chemometric tool that aids in identifying and visualizing the sources of variation in a data set, which is crucial for

distinguishing the patterns unique to each type of corrosive damage.^[14] For instance, the combination of FTIR spectroscopy and PCA has been beneficial for differentiating between the effects of sulphuric, hydrochloric, and nitric acids on textile fibre samples.^[14] The software's capacity to recognize minute differences in the spectral fingerprints reduces human error and, therefore, ensures more reliable results.

Some recent studies demonstrate the potential of emerging approaches, such as Artificial Intelligence (AI), to aid in the forensic analysis of corrosive damage. More specifically, Machine Learning (ML) algorithms can be applied to spectral data to identify the nature of chemical interactions and distinguish between different compounds.^[13,14] Therefore, such an approach can be used to determine the composition of a sample with minimal human interventions. Although the application of AI- and ML-assisted forensic analyses is still developing, such techniques will eventually provide significant benefits in terms of accuracy and efficiency.

Another significant innovation in recent years is the introduction of portable versions of analytical instruments for the examination of corrosive damage. In particular, the handheld Fourier Transform Infrared (FTIR) and Raman spectroscopy devices enable rapid screening of the evidence without the need for destructive sampling, thus eliminating the delays caused by waiting for laboratory results.^[11-14] Combined with the use of AI and advanced analytical software, these developments will continue to influence the field of forensic analyses of chemical damage, which will ultimately result in more efficient processing of evidence.

In summary, the review of the relevant literature reveals an overall trend towards the transition from traditional analytical methods to more advanced approaches. Although each technique has demonstrated its advantages, the application of multiple methods in combination has been found to be more reliable. The integration of diverse strategies, including those relying on infrared spectroscopy, SEM, XRD, chemometric software, and AI, has been beneficial for obtaining comprehensive results in the forensic examination of corrosive damage.

2.4 Emerging Trends in Forensic Corrosive Analysis

Recent advances in forensic science have seen a shift away from traditional approaches to corrosive analysis, as researchers explore innovative multidisciplinary methods that emphasize the use of spectroscopy, microscopy, chemometrics, and computational approaches to reveal the nature of substances involved in corrosive incidents.^[4-14] Such studies have helped produce more objective findings while simultaneously boosting the overall accuracy of forensic examinations. Below are some of the most interesting innovations and trends in the field of forensic corrosive analysis.

First and foremost, the use of chemometric methods for analyzing spectra and distinguishing between types of damage has seen a significant increase in the last few years. Traditional approaches to spectroscopy rely on the ability of the researcher to interpret the results, which means that a miscalculation or misjudgment on their part can lead to erroneous conclusions. On the other hand, statistical tools, such as the Principal Component Analysis, can help recognize patterns within a set of spectra. For instance, a combination of FTIR spectroscopy and PCA has proven instrumental in differentiating between sulphuric, hydrochloric, and nitric acids, which have damaged textile fibres.^[14] Such an approach allows producing more objective results and reduces the possibility of analyst bias.

The field is also seeing a rapid rise in the use of artificial intelligence and machine learning to analyze data and identify patterns that could be used to classify different types of damage to materials.^[13,14] At the moment, most of the research into the applications of AI in the field focuses on using it as a tool to accelerate the analysis and classification of various types of damage.^[13,14] While the use of such technologies in the field of corrosive analysis is still experimental, the trends suggest that they will soon become a crucial element of all forensic examinations due to their potential to eliminate much of the guesswork involved at the moment.

Recent technological improvements have also seen the introduction of more affordable and portable devices, such as handheld FTIR and Raman spectrometers. They can be used to gather crucial pieces of information at the scene of the crime, thus helping the investigators determine what kind of substances were involved before they transport the evidence to the laboratory.^[11-14] In general, portability is a significant advantage in forensic science, as it makes the research process more efficient while reducing the possibility of mistakes.

Most researchers suggest that effective corrosive analysis requires a multidisciplinary approach and the combination of various traditional analytical methods, including spectroscopy and microscopy.^[4-7,11-14] In particular, computational chemistry, AI, and chemometrics are essential for identifying the nature of damage and determining its impact on the properties of the affected material. Overall, the general trends in the field suggest that corrosive analysis will continue to evolve rapidly in the future, embracing innovative technologies and approaches to improve accuracy and efficiency.

3. METHODOLOGY

The review was conducted using the systematic literature research method to assess the forensic examination of commonly used corrosive substances on different matrices and analytical methods used for their identification. The data for this study were extracted from scholarly articles, review papers, books, conference

proceedings, and technical reports. The databases searched include Google Scholar, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, PubMed, and Forensic Science journals.^[2,10]

The search strategy involved using keywords such as corrosive substances, acid attack, vitriolage, forensic examination, textile damage, sulphuric acid, hydrochloric acid, nitric acid, FTIR, ATR-FTIR, SEM, Raman spectroscopy, GC-MS, PCA, and crime scene reconstruction in combination with Boolean operators (AND, OR). Articles with research content on the effects of commonly used corrosive substances on different forensic matrices and modern analytical methods used in their examination were preferred.^[4-14]

Peer-reviewed publications with articles in English on corrosive examination, fibre degradation, and analytical methods were included while duplicates, non-forensic studies, and research with inadequate information were excluded. Most of the selected articles for this review were published between 2018 and 2026. A few of the papers used for this review were published before 2018 and were considered significant to the study.^[11]

The screening process involved identifying relevant studies by reading the titles and abstracts followed by a full-text screening and data extraction. Data extracted were grouped into themes such as corrosive substances, effects on different matrices, analytical methods, forensic examination, research gaps and future prospects. Analytical methods such as FTIR, ATR-FTIR, SEM, Raman spectroscopy, GC-MS, XRD, XPS and PCA were critically examined.^[4-14]

Because of the differences in research design, substrates, concentrations, and analytical methods examined in the selected articles, a qualitative descriptive synthesis approach was used. This approach allowed comparing the findings of the selected articles, identifying research gaps, and summarizing the body of knowledge on the forensic examination of commonly used corrosive substances on different matrices.

4. SYNTHESIS OF LITERATURE

Based on the review, the literature revealed that commonly encountered corrosive substances cause distinctive physical, chemical and microscopic alterations to various forensic matrices. The severity and nature of these changes were determined by the specific chemical and/or physical properties of the corrosive substance, its concentration, exposure time, and the characteristics of the exposed material. The most commonly studied substances were sulphuric, hydrochloric and nitric acids, which are frequently involved in acid attacks and other forms of forensic relevance.^[8-10]

The most examined materials were textile substrates,

with natural fibres such as cotton and wool being particularly susceptible to the effects of exposure. Treatment with sulphuric acid resulted in dehydration, carbonization, fibre swelling and breakage as well as fragmentation and structural damage to the fibres. Hydrochloric acid, on the other hand, caused hydrolytic degradation and fibre weakening, while nitric acid resulted in characteristic yellowing of the material with loss of integrity. In addition to the visual inspection, most of the damage was evident even when laundered, thus enhancing the evidential value of such clothing.^[8,9] The examined synthetic fibres, including polyester and nylon, generally showed superior resistance to the tested acids, although prolonged exposure resulted in melting, shrinkage and surface wrinkling. In blended materials, the observed effects were inconsistent between the different fibre types, with natural fibres generally being more susceptible to degradation.^[5,8,14]

The reviewed literature also demonstrated that other common forensic matrices including paper, wood, carpet, rubber and biological tissues also exhibit characteristic signs of exposure to various acids. With the exception of biological tissues that generally showed coagulative necrosis, severe burning sensation, dehydration and permanent tissue damage, other porous materials generally retained corrosive substances on their surfaces for extended periods of time.^[9-12]

The reviewed articles indicated that Fourier Transform Infrared Spectroscopy (FTIR) and Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR) were the most commonly used techniques for the identification of chemical changes associated with exposure to corrosive substances. Both methods allow rapid analysis without damaging the sample, thus facilitating consistent and conclusive results.^[1,3,11,12] On the other hand, Scanning Electron Microscopy (SEM) allowed the examination of the physical changes to the examined materials, including fibre swelling, surface cracks, splitting and fragmentation. Raman spectroscopy, X-ray diffraction (XRD) and X-ray Photoelectron Spectroscopy (XPS) provided additional insight into the structural and chemical alterations to the examined materials.^[4,6,7,9] More recently, there is a growing body of research utilizing FTIR combined with Principal Component Analysis (PCA) to improve the accuracy of discrimination between sulphuric, hydrochloric and nitric acids, thus enhancing the reliability of the results while minimizing the need for extensive data interpretation.^[14]

In general, the reviewed articles demonstrated a shift away from traditional visual inspection towards more advanced spectroscopic, microscopic and chemometric techniques that can be utilized in a variety of forensic contexts, including identification of the corrosive substances, characterization of the damage and recreation of the event.

Table 1: Summary of the forensic effects of commonly used corrosives on different matrices.

Corrosive Agent	Matrix	Major Characteristics Damage	Forensic Significance	Reference
Sulphuric acid	Cotton	Carbonization, dehydration, fibre fragmentation, hole formation	Identification of acid type and reconstruction of acid attacks	[8,9]
Hydrochloric acid	Cotton/Wool	Hydrolysis, weakening, tearing	Differentiation from other mineral acids	[8,14]
Nitric acid	Cotton/Wool	Yellow discoloration, oxidation, loss of fibre strength	Characteristic nitration evidence	[8,14]
Sulphuric acid	Polyester/Nylon	Melting, shrinkage, surface deformation	Identification of synthetic fibre damage	[8,9]
Mineral acids	Blended fabrics	Differential degradation of natural and synthetic fibres	Fibre composition determination	[8]
Corrosives	Biological tissues	Coagulative necrosis, severe burns, dehydration	Medico-legal interpretation	[9,10]

Table 2: Analytical techniques commonly employed in forensic corrosive examination.

Technique	Major Application	Advantages	Reference
FTIR	Chemical characterization	Rapid, non-destructive, minimal sample preparation	[1,3,4]
ATR-FTIR	Surface analysis of damaged materials	Direct examination without sample preparation	[11,12]
SEM	Fibre morphology	High-resolution microscopic examination	[4,6,9]
Raman Spectroscopy	Molecular characterization	Complementary chemical information	[6]
GC-MS	Chemical residue identification	Highly sensitive for volatile compounds	[5]
XRD	Crystallinity analysis	Structural characterization	[4,7]
XPS	Surface elemental analysis	Detection of chemical bonding changes	[6]
FTIR-PCA	Acid discrimination	Objective classification and high analytical accuracy	[14]

5. DISCUSSION

The present review demonstrates that modern analytical techniques have significantly improved the forensic examination of corrosive substances. The reviewed studies show that sulphuric acid, hydrochloric acid, and nitric acid produce characteristic physical, chemical, and microscopic changes that assist in identifying the corrosive agent and reconstructing criminal events.^[8-10]

The extent of damage depends largely on the substrate. Natural fibres such as cotton and wool undergo dehydration, hydrolysis, carbonization, and fibre fragmentation, whereas synthetic fibres such as polyester and nylon generally exhibit melting, shrinkage, and surface deformation because of their greater chemical resistance.^[5,8,9] These differences are valuable for forensic interpretation, and damaged clothing often retains characteristic acid-induced changes even after laundering, making it an important source of evidence.^[8,9]

The literature also highlights the importance of advanced analytical techniques in forensic investigations. FTIR,

ATR-FTIR, SEM, Raman spectroscopy, GC-MS, XRD, and XPS provide detailed chemical and structural information that cannot be obtained through routine visual examination alone.^[4-7,11-14] FTIR and ATR-FTIR enable rapid, non-destructive identification of chemical changes, while SEM reveals microscopic fibre damage.^[4,6,9] Recent studies have shown that combining FTIR with Principal Component Analysis (PCA) improves the differentiation of sulphuric, hydrochloric, and nitric acids by increasing analytical accuracy and reducing subjective interpretation.^[14] Artificial Intelligence (AI) and Machine Learning (ML) are also emerging as promising tools for automated analysis of forensic spectral data.^[13,14]

Despite these advances, several limitations remain. Most studies have been conducted under controlled laboratory conditions, which may not accurately represent real crime scenes where environmental factors influence corrosive residues and substrate degradation.^[5,8,9] The lack of standardized analytical protocols and comprehensive reference databases also limits consistency among forensic laboratories.^[2,14] In addition, current

research has focused mainly on strong mineral acids and textile materials, while alkaline corrosives, mixed chemical agents, and other forensic matrices such as plastics, metals, glass, and electronic devices remain insufficiently investigated.

Overall, forensic corrosive examination has evolved from conventional visual assessment to multidisciplinary analytical approaches integrating spectroscopy, microscopy, chromatography, and chemometric analysis. Future research should focus on standardized analytical methods, expanded reference databases, portable analytical instruments, and AI-assisted interpretation to improve the accuracy, reliability, and forensic application of corrosive examinations.^[2,10,13,14]

6. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite the progresses in the field, the current forensic examination of corrosive substances is characterized by several limitations related to reliability, reproducibility, and standardization.

6.1 Research Gaps

A significant problem in the current forensic analysis of corrosive substances is the absence of standardized protocols, leading to inconsistencies and varied interpretations.^[2] The majority of the literature deals with sulfuric acid, hydrochloric acid, and nitric acid, while the effects of more commonly found alkalis, complex, and mixed corrosive systems, commercial cleaning liquids, and industrial acids were poorly studied.^[8-10,14]

Most of the studies are focused on the impact of various substances on textile fibers, including cotton, wool, polyesters, and mixed materials. The role of corrosive liquids on such materials as leather, plastics, metals, glass, concrete, paint, electronics, and other related substrates, was rarely subject to detailed analysis.^[8,9,14] Moreover, the majority of the aforementioned studies were conducted under ideal laboratory conditions, whereas the real-world environment is significantly more complex, which complicates the analysis.^[5,8,9] Another limitation relates to the absence of comprehensive reference spectral databases that could be used for the rapid identification of corrosive substances.^[4,6,14] Advanced computational methods such as chemometrics and artificial intelligence have not been widely used, despite their potential to improve the accuracy and efficiency of the identification process.^[14]

6.2 Future Perspectives

The future of forensic examination of corrosive substances will be defined by the development of standardized protocols for sample collection, analysis, interpretation, and reporting, which could gain wide acceptance within the scientific community and the court system.^[2] To ensure reliability, large-scale experiments should be conducted to generate sufficient reference data on the effects of different corrosive substances on

diverse substrates and environments. It is also critical to involve other analytical techniques, including FTIR, ATR-FTIR, SEM analysis, RAMAN Spectroscopy, GC-MS, XRD, XPS, chemometric analysis, and others, in order to obtain more accurate and reliable results.^[4-6,11-14]

In the long term, artificial intelligence and machine learning could be used to automate and improve the identification process.^[14] Finally, the increased use of portable and non-destructive FTIR and RAMAN spectrometers could make forensic analysis more efficient and accessible, even at the scene of the crime. Overall, the collaboration between different experts, including forensic scientists, analytical chemistry experts, material experts, and law enforcement, should be strengthened to ensure continuous progress in forensic examination of corrosive substances.

7. CONCLUSION

The present review article analyzed the existing literature data on the forensic examination of commonly encountered corrosive substances on different substrates and the analytical techniques used for their identification. The reviewed research reports confirmed that the action of strong mineral acids, especially sulphuric, hydrochloric, and nitric ones, leads to the formation of typical physical, chemical, and microscopic features helpful in establishing the identity of the corrosive agent, criminal case reconstruction, and medico-forensic expertise.^[8-10]

Cloth fabrics were the most widely studied objects of forensic examination. It refers to the fact that the damage caused by acids, alkalis, or other aggressive substances is usually visual and can be revealed even after the clothing is washed or worn multiple times. Most natural fibers, including cotton and wool, tend to hydrolyze, dehydrate, carbonate, and decompose when exposed to diluted or concentrated mineral acids, while synthetic fibers generally exhibit melting, shrinking, and surface defects like holes, cracks, and burns.^[5,8,9,14]

The review identified the analytical techniques that can be used in the forensic examination of various corrosive substances. Specifically, Fourier-transform infrared (FTIR), attenuated total reflectance Fourier-transform infrared (ATR-FTIR), scanning electron microscopy (SEM), Raman spectroscopy, gas chromatography-mass spectrometry (GC-MS), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and chemometrics are the most promising methods for the identification of the corrosive agents and the examination of their impact on different materials.^[1,3-7,11-14] However, the literature data indicate that research studies of forensic interest concerning the physicochemical properties of corrosion products are limited to the use of particular analytical techniques, a narrow range of corrosive substances and materials, and non-variable environmental conditions.^[2,10,14]

To summarize, the review demonstrated that forensic

corrosive examinations have become a multidisciplinary field of forensic science that integrates various methods of spectroscopy, microscopy, chemistry, physics, and materials science. Further research is needed to develop standardized procedures for the chemical identification of corrosion products using advanced analytical instrumentation, including transportable devices and artificial intelligence algorithms.^[2,13,14]

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