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Quality Assessment of Papers Using Hyperspectral Imaging and Non-Imaging Techniques: A Review

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Abstract: *The preservation of both ancient and modern paper documents involves analytical procedures that can determine their status without physical destruction. This review assesses the use of Hyperspectral Non-Imaging Spectroscopy (HNIS), alongside Hyperspectral Imaging (HSI) and other spectroscopic methods, in the identification of paper composition, quality and deterioration. This work offers insights into the detection of chemical and structural variations like acidity, oxidation, fungal activity, and additive presence in non-contact analysis based on studies conducted between 2001 and 2025. HNIS offers a high spectral resolution and sensitivity to small chemical differences, and is suitable to delicate artefacts, whereas HSI can map large areas complementary to HNIS. The implementation of machine learning to predict degradation, classify, and estimate chronologically is also discussed in the article. Some of the most notable issues determined include the lack of common spectral reference collections, inadequate combination of real-time environmental information, and inadequate variance of training data. The offered HNIS-ML integration framework provides a scalable, non-invasive method of early damage detection and informed preservation planning in museums, libraries and archives.*

Keywords: *Remote sensing, Hyperspectral Non-Imaging Spectroscopy, Hyperspectral Imaging, Paper degradation, Spectral reflectance, non-destructive analysis, Historical paper, Machine learning.*

I. INTRODUCTION

The use of paper as a tool of communication, documentation, education and creative expression has been a part and parcel of human society since time immemorial. Papermaking has been introduced to develop significantly over time. Paper sheets were traditionally made out of tree bark, scraps of fabric and natural fibres [1]. Paper is nowadays produced in mills using chemically treated wood pulp, often supplemented with a number of additives and surface finishes [2]. The quality and durability of paper, the manufacturing processes and its long-term preservation properties depend on the raw materials used in the production of paper [3].

Methods of evaluating the status of paper without damaging it are in increasing demand, especially in libraries, museums, archives, and trade. Conventional methods like pH analysis, tensile strength test and fibre microscopy generate correct data, yet tend to be lengthy, tedious, and inappropriate with large populations [4, 5].

Non-contact alternatives have been developed such as Hyperspectral Non-Imaging Spectroscopy (HNIS) which is a powerful technique. In contrast to traditional imaging, HNIS records spectral detail at a single point or a small area of a large spectral range, covering ultraviolet to visible wavelengths up to near-infrared. This allows scientists to develop an in-depth chemical and physical characterization of paper without physical contact. HNIS, in combination with machine learning, can quickly classify the type of paper and detect early signs of wear and tear, which makes it a precious tool in environmental conservation and quality assurance in numerous industries [6, 7].

A. The History of Papermaking

Paper which has profound cultural and technological implications has been significantly transformed into a different form over the course of the human history. First manufactured in ancient China and Egypt using natural fibres hemp, flax, and mulberry bark, sheets were handmade, producing materials that lasted long, had unique textures and structural properties. With the advent of industrial papermaking in the 19th century, wood pulp emerged as the main raw material. This facilitated the mass-scale production but also came along with new challenges, such as increased acidity and deterioration rates [3].

The history of papermaking development has been characterized by the successive stages of development of the raw materials and technology, as well as by the influence of economic and cultural factors on the craft. Although a great deal of effort has been focused on the conservation of old documents and manuscripts, relatively little effort has been devoted to the systematic study of the actual paper, its chemical makeup, physical structure, and the changes taking place in these characteristics over time [5].

To fill this gap, a more thorough knowledge of material properties and predicting stability over the long term is necessary. Hyperspectral non-imaging spectroscopy can help in this respect, as it can be used to analyze and compare paper of various epochs without the threat of any damage. These analytical abilities will help in gaining a more accurate interpretation of material science in historical contexts and help in coming up with more efficient preservation strategies [6, 7].

B. Evolution of Paper Composition

The construction materials and processes of paper have been altered considerably since the 1800s, and the effects of these changes directly affect the quality and durability of paper. Linen and cotton rags were used to produce most paper in the 19th century. The sizing agent was gelatin to enhance durability and ink absorbency, with fillers (including clay) being seldom used [8]. The process of bleaching could be attained naturally by exposure to sunlight. Consequently, paper manufactured during this period were generally stable and chemically resistant, but not immune, such as being susceptible to microbial reaction in gelatin sizing and degradation by water contamination [9].

The early 20th century was a major transition in the use of traditional rag-based materials to less costly and more plentiful wood pulp. This shift entailed the use of chemical and mechanical pulp treatment. Despite a continued presence of rag, fibres of wood became the most common source. Gelatin was supplanted by rosin-alum systems as the main sizing process. Calcium carbonate and clay were used as common additives and chlorine-based bleaching was popularly adopted. Acidic alum and heavy-metal dyes made paper during this era more frail, likely to turn yellow, and susceptible to permanent damage [10].

By the 2000s, there was more development in papermaking, where more reliance was made on wood pulp and recycled fibres. Alkyl Ketene Dimer (AKD) and Alkyl Succinic Anhydride (ASA) were used as synthetic sizing agents to replace older techniques due to enhanced stability and water resistance. Titanium dioxide and calcium carbonate became the standard fillers, brightness and print performance improved. Bleaching was also developed in reaction to environmental issues, with Elemental Chlorine Free (ECF) and Total Chlorine Free (TCF) processes that employed ozone and hydrogen peroxide becoming the norm. Papers made in modern times tend to be more alkaline, brighter and stronger but performance remains subject to influence by contaminants in the recycled pulp [11, 12].

By the 2020s, the papermaking industry has grown to use new alternative fibres, such as bamboo and agricultural waste, and bio-based and synthetic sizing agents [13]. New fillers like nanocellulose and modified calcium carbonate can be used to enable refined paper properties. Enzyme-assisted, peroxide-based TCF processes have become the most common form of bleaching [12, 13]. Although the given developments can be considered significant improvements, the issues of environmental contaminants, such as microplastics and per- and polyfluoroalkyl substances (PFAS) present in the recycled pulp have also been mentioned, which casts doubt on the safety and recyclability. Even though the modern papers are designed with a purpose to fulfill a particular task and they are sustainable, the general quality of the product is determined by the origin of raw materials and the harshness of processing techniques [13, 14].

TABLE I: EVOLUTION OF PAPERMAKING MATERIALS AND QUALITY (1800s–2020s)

Era	Fibres	Sizing	Fillers	Bleaching	Hazardous Substances	Paper Quality
1800s	Linen & cotton rags	Gelatin	Clay/chalk (minimal)	Sunlight or none	Microbial contamination in gelatin	Durable, high quality, stable
1900s	Wood pulp & some rags	Rosin-alum and gelatin	Clay and calcium carbonate	Chlorine-based	Alum acidity, chlorine residues, metal dyes	Less durable, acidic, prone to yellowing
2000s	Wood pulp & recycled fibres	AKD, ASA (synthetic)	Calcium carbonate, TiO ₂	ECF/TCF (ozone, peroxide)	Bleaching residues, recycled contaminants	Consistent, bright, alkaline, durable
2020s	Wood, recycled, non-wood (bamboo)	Synthetic, bio-based	Nanocellulose, modified calcium carbonate	TCF (enzymes, hydrogen peroxide)	PFAS & microplastics in recycled pulp	Purpose-designed; variable quality

C. Hyperspectral Imaging (HSI) and Hyperspectral Non-Imaging Spectroscopy (HNIS)

Hyperspectral Imaging (HSI) and Hyperspectral Non-Imaging Spectroscopy (HNIS) are two complementary techniques of analysis of materials. HSI obtains spectral data in each pixel over a two dimensional spatial field and results in a three dimensional hypercube, which covers both 2-D spatial and 1-D spectral dimensions [15]. HSI can measure visual and chemical characteristics on a pixel scale with many narrow, closely-spaced spectral bands, and therefore, it is a crucial instrument in heritage science to uncover faded text, hidden layered objects and chemical decay - without touching the object [16, 17].

HNIS in contrast uses fibre-optic or non-contact probes to collect high-resolution spectra at localised points. Although it does not map space it is more spectral in depth and sensitivity and thus best suited to analyzing cellulose, lignin, filler and degradation signs in paper. HSI and HNIS are used collaboratively to give extensive graphic coverage over an area and localized chemical analysis, respectively. The similarities of the two methods include the fact that they are non-destructive, contactless, and informational rich [18]. Key capabilities include:

- Identification of fibre types (e.g. cotton, flax, wood pulp)
- Detection of additives including gelatin, rosin, and calcium carbonate
- Identification of early signs of chemical degradation
- Discrimination between historical and modern paper based on spectral signatures [16, 18]

TABLE II: COMPARISON OF HYPERSPECTRAL IMAGING AND HYPERSPECTRAL NON-IMAGING SPECTROSCOPY

Aspect	Hyperspectral Imaging (HSI)	Hyperspectral Non-Imaging Spectroscopy (HNIS)
Data captured	Spectral + spatial information	Spectral information only
Primary use case	Mapping material properties across a surface	Analysing a single point or small area in detail
Application to paper	Detecting degraded regions, mapping large document areas	Examining specific paper composition or localised degradation

D. Detection of Degradation Types

Hyperspectral Non-Imaging Spectroscopy can be especially useful in preventative conservation since it can detect the chemical and structural changes in paper at the earliest stages of their development. The method is more particularly useful in identifying oxidation, acidity, fungal growth, and fibre degradation by unique spectral indicators in UV-Vis and NIR. Gupta and Singh (2021) showed that hyperspectral data are capable of differentiating between oxidised, fungus-infected, and chemically modified samples, and can be used to classify papers based on the level of degradation with machine learning models [7]. Spectral shifts can also be measured as a result of environmental stressors, like humidity, heat, and pollution. Pretzel and Fearn (2020) demonstrated that the combination of spectroscopy with environmental surveillance allows relating these variables to the paper degradation patterns [50]. Also, UV-Vis and NIR may be employed to determine yellowing agents and changes in cellulose and lignin content, whereas the spectral decay pattern may be used to determine the presence of free radicals when chemiluminescence is employed. In general, HNIS facilitates proactive conservation by allowing one to identify risks prior to structural damage, thus improving the stability of collections in the long term [50].

II. LITERATURE REVIEW

The overall literature review offers the background to learn about the current level of research on hyperspectral analysis and other spectroscopic techniques to examine paper quality. Studies using hyperspectral imaging and non-imaging methods of paper conservation have increased significantly in the past decades. These non-invasive techniques aid in research into the composition of materials, how they deteriorate, and how the environment affects historical documents. The next section discusses the major works, their methodology, and the key results that have helped to advance the sphere.

TABLE III: SUMMARY OF KEY LITERATURE ON HYPERSPECTRAL TECHNIQUES FOR PAPER ANALYSIS

Sr. No	Author(s)/Year	Title	Techniques	Key Result / Contribution
1	Ali et al. 2001 [21]	Near-Infrared Spectroscopy for Monitoring Artificial Aging of Paper	NIR spectroscopy	Monitored aging of paper treated by elevated temperature, observing carbonyl/carboxyl peak development.
2	Chabries 2003 [22]	Enhancing the Legibility of Faint or Burnt Documents	Multispectral imaging (MSI)	Used MSI for enhancing legibility of faint or burnt documents.
3	Attas et al. 2004 [23]	Hyperspectral Imaging for Enhanced Visualization of Historical Documents	HSI, 400-900 nm	Demonstrated HSI for legibility enhancement in historical texts; validated integration of NIR and UV-Vis.
4	Bonifazzi 2005 [24]	Hyperspectral Imaging for Artwork Inspection	HSI	Focused on high spatial resolution for detailed analysis of small sections of paintings.
5	Havermans 2005 [25]	Near-Infrared Spectroscopy as a Tool for the Identification of Paper and Inks in Conservation Research	NIR spectroscopy	Identified paper and ink components, discriminated paper compositions, and tracked aging characteristics.
6	Scholten et al. 2005 [26]	Hyperspectral Imaging for Plant Disease Detection: A Study on Spectral Variability	HSI (single point measurements)	Identified reliability challenges associated with single-point measurements in reflectance curves.
7	Fischer & Kakoulli 2006 [27]	Multispectral and Hyperspectral Imaging Technologies in Conservation: Current Research and Potential Applications	HSI	Applied HSI for cultural heritage analysis including pigment identification and underdrawing detection.
8	Rychly et al. 2006 [28]	A Chemiluminescence Study of Madder Lakes on Paper	Chemiluminescence (CL), PICL, NIR	Studied photodegradation of madder lake-based watercolours on paper, linking chemiluminescence to free radical degradation.
9	Strlic et al. 2008 [29]	Non-Destructive Characterization of Historical Paper Using NIR Spectroscopy and Chemometrics	NIR spectroscopy + chemometrics	Developed non-destructive NIR instrument for determining chemical and mechanical properties (tensile strength, pH) of historical paper, predicting publication year with high accuracy.
10	Barbin et al. 2012 [30]	Hyperspectral Imaging for Quality Assessment of Food Products: A Review	HSI	Applied HSI in food quality assessment; methodologies transferable to paper analysis for predicting quality attributes.
11	Bioucas-Dias et al. 2012 [31]	Hyperspectral Unmixing: Geometrical, Statistical, and Sparse Regression-Based Approaches	Hyperspectral unmixing techniques	Provided a comprehensive review of spectral unmixing techniques for decomposing mixed pixel spectra.
12	Boldrini et al. 2012 [32]	Hyperspectral Imaging: Best Practice, Performance and Pitfalls for In-Line and On-Line Applications	Hyperspectral industrial monitoring	Outlined best practices for in-line and on-line HSI systems, including calibration and data analysis for quality control.
13	Vo-Dinh et al. 2014 [33]	Multivariate Optical Computing for Spectroscopic Analysis	Multivariate Optical Computing	Presented a framework for portable spectral classification with faster processing and improved signal-to-noise ratio.
14	Cucci, Delaney et al. 2016 [34]	Reflectance Hyperspectral Imaging for Investigation of Works of Art	HSI	Applied HSI for cultural heritage analysis including old master paintings and illuminated manuscripts.
15	Calvini & Gorassini 2017 [35]	FTIR and Raman Spectroscopy for Non-Invasive Analysis of Historical Documents	FTIR, Raman spectroscopy	Reviewed scalable non-destructive methods for archival conservation.
16	Giacometti et al. 2017 [36]	Visual Enhancement of Old Documents with Hyperspectral Imaging	HSI	Used HSI for undertext recovery in historical documents, enhancing legibility of faded or hidden text.
17	Sandak et al. 2017 [37]	Hyperspectral Imaging of Weathered Wood Samples in Transmission Mode	HSI	Demonstrated early degradation mapping with HSI on weathered wood, investigating kinetics of degradation rate.
18	Gewali et al. 2018 [38]	Machine Learning Based Hyperspectral Image Analysis: A Survey	Survey of ML algorithms applied to HSI	Comprehensive survey of ML techniques for HSI tasks including land cover classification, target detection, & unmixing.
19	Smith & Taylor 2018 [40]	Non-Imaging Spectroscopy for Material Analysis of Historical Artifacts	UV-Vis, NIR spectroscopy	Detected cellulose, lignin, and other paper components; demonstrated non-invasive chemical profiling of historical artefacts.
20	Lehnert et al. 2019 [39]	The hsdar Package: Hyperspectral Data Analysis in R	HSI data processing	Developed the hsdar R package for efficient storage and analysis of large hyperspectral datasets, integrating machine learning tasks.

21	De Viguier et al. 2019 [41]	Hyperspectral Imaging for the Analysis of Photographic Emulsions	HSI (400-900 nm)	Used HSI to analyse photographic emulsions, providing enhanced characterisation of paint and coating materials.
22	Gabrieli et al. 2019 [42]	Diffuse Reflectance Spectroscopy for In-Situ Characterization of Artists' Materials	Diffuse reflectance spectroscopy	Applied for in-situ characterisation of artists' materials in museum and archaeological settings.
23	Hao Yang et al. 2019 [43]	Rapid Determination of Holocellulose and Lignin in Wood by NIR Spectroscopy and Kernel Extreme Learning Machine	NIR, chemometrics (PLS, LSSVM, BPNN, KELM)	Developed rapid method for determining holocellulose and lignin in pulp wood, with KELM showing best prediction performance.
24	Tonazzini et al. 2019 [44]	Multispectral and Hyperspectral Document Restoration: A Review	MSI/HSI	Applied for digital restoration of historical manuscripts using preprocessing and text retrieval techniques.
25	De Viguier et al. 2019 [45]	Principal Component Analysis of Spectral Data: A Contribution to the Knowledge of Materials in Works of Art	PCA on spectral data	Applied PCA to spectral data for dye layer separation and improved material distribution analysis in artworks.
26	Wang et al. 2019 [46]	Remote Sensing in the Preservation of Cultural Heritage Materials	Remote sensing	Used environmental data to track degradation; promoted integration of remote sensing with material analysis for archival facilities.
27	Barrett & Stullich 2020 [47]	Overview of Hyperspectral Techniques in Heritage Conservation	Hyperspectral imaging	Identified pigments and degradation products; emphasised non-invasive, long-term monitoring.
28	Jones et al. 2020 [48]	Understanding Multispectral Imaging of Cultural Heritage: Best Practice in MSI Analysis	Multispectral Imaging (MSI)	Reviewed best practices for MSI of cultural heritage, identified inconsistencies in documentation, and proposed improvements for reproducibility.
29	Orazi 2020 [49]	Mid-Wave Infrared Reflectography and Thermography for the Study of Ancient Books: A Review	MWIR reflectography	Used MWIR reflectography to evaluate ink and bindings in ancient books, revealing hidden texts and structural elements.
30	Pretzel & Fearn 2020 [50]	Environmental Impacts on Archival Papers: A Spectroscopic Approach	Spectroscopy + environmental monitoring	Linked temperature and humidity to spectral degradation markers; suggested optimal storage guidelines.
31	Rasti et al. 2020 [51]	Feature Extraction for Hyperspectral Image Classification: A Review	Deep learning for hyperspectral feature extraction	Reviewed deep learning for hyperspectral feature extraction, enhancing class separability and integrating spatial information.
32	Gupta & Singh 2021 [7]	Spectral Analysis of Aging and Deterioration in Historical Papers	Hyperspectral spectroscopy	Identified oxidation, fungal growth, and chemical changes in aged papers; enabled classification of degradation levels using machine learning.
33	Ramanathan & Iyer 2022 [52]	Advances in Hyperspectral Non-Imaging for Material Characterization	HNIS + machine learning	Proposed ML models for heritage science applications, demonstrating HNIS effectiveness for fragile artefacts.
34	Wang et al. 2022 [53]	Tensor Decomposition Techniques for Hyperspectral Image Restoration	Tensor decomposition	Introduced tensor decomposition for large HSI datasets, addressing noise and enhancing analytical precision.
35	Strlic et al. 2023 [54]	Non-Destructive Dating of Paper Books Using Near-Infrared Spectroscopy and Machine Learning	NIR, supervised ML (PLS, RF, kNN, LSSVM, CNN)	Predicted publication year of paper books (1851-2000) with up to 2 years accuracy, surpassing previous non-destructive methods.
36	Wan G et al. 2025 [55]	Hyperspectral Imaging Technology for Nondestructive Identification of Quality Deterioration in Fruits and Vegetables: A Review	HSI, machine learning	Summarised HSI applications in non-destructive quality assessment; highlighted multi-sensor fusion and AI for industrial applications.

The following table is a chronological account of important research that has been carried out in the field of hyperspectral analysis in preserving paper. The discipline has developed out of an early history of spectroscopic studies to an analytical discipline.

In 2005 notable work was done in the area of high-resolution HSI to detect fine structural details in paintings by Bonifazzi, the use of NIR spectroscopy to identify paper and ink constituents without destructive sampling by Havermans and the issue of reliability of data in single-point measurements by Scholten et al. Fischer and Kakoulli (2006) also contributed to the sphere and mentioned that HSI was effective in the identification of pigments and the detection of the underdrawing in historical objects.

The contribution was made by Strlic et al. (2008) who created a near-infrared spectroscopic device, as part of the SurveNIR programme, which made it possible to determine pH, tensile strength, and publication date of historical paper using chemometrics. Smith and Taylor (2018) have shown that non-imaging UV-Vis and NIR spectroscopy can offer quick chemical profiling of the old media and determine the cellulose and lignin and other paper constituents without having to physically sample them.

The scope of HSI application was expanded as De Viguerie et al. (2019) utilized visible-range HSI (400-900 nm) to examine photographic emulsions and complex surfaces, not restricted to manuscripts and paintings. Gabrieli et al. (2019) used diffuse reflectance UV-Vis-NIR spectroscopy to identify pigments and binder on site in a museum setting. Hao Yang et al. (2019) applied NIR spectroscopy and machine learning to measure the content of holocellulose and lignin in pulp wood quickly, which can be applied in the evaluation of archival paper. Tonazzini et al. (2019) studied the multispectral and hyperspectral techniques in the restoration of digital manuscripts, and De Viguerie et al. (2019) used PCA on spectral data to distinguish the layers of dye and categorize the materials in the multilayer system. Wang et al. (2019) highlighted the importance of satellite remote sensing and spectroscopy in the measurement of environmental variables, such as temperature, humidity, and pollution, which influence paper preservation.

Barrett and Stullich (2020) surveyed HSI uses in the field of cultural heritage conservation, which validated its usefulness in pigment identification, degradation tracking, and non-invasive observation. Jones et al. (2020) suggested standardised procedures to multispectral imaging, highlighting the need to use uniform spectral bands and metadata to ensure reproducibility. Orazi (2020) emphasized the usefulness of MWIR reflectography and thermography in revealing concealed texts and structural features of old manuscripts. Pretzel and Fearn (2020) linked spectral indicators to environmental stressors as predictors of paper degradation and Rasti et al. (2020) surveyed deep learning algorithms, such as CNNs and autoencoders, to enhance hyperspectral features extraction and classification. Gupta and Singh (2021) combined hyperspectral spectroscopy with machine learning in identifying degradation signs such as oxidation, fungi, and chemical changes to develop a non-invasive conservation model.

Ramanathan and Iyer (2022) further the argument of HNIS in heritage science and suggest machine learning models to classify and characterise sensitive artefacts. Wang et al. (2022) used the method of hyperspectral image denoising and restoring using tensor decomposition, which enhances the accuracy of the analysis when the amount of data is large. Strlic et al. (2023) confirmed that NIR spectroscopy and supervised machine learning were able to document date with two-year accuracy, which is a great breakthrough in authenticity verification. Lastly, although Wan et al. (2025) conducted more experiment on food preservation, they showed how HSI and machine learning, as well as sensor fusion, could be used effectively to track degradation, which can be directly transferred to aged paper monitoring.

III. PROPOSED METHODOLOGY

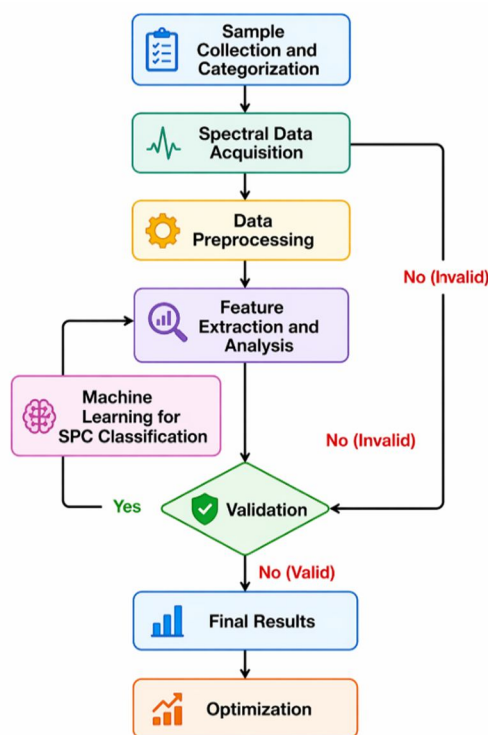


Fig. 1. Proposed Methodology

The approach that was developed in this research offers a logical framework to the implementation of HNIS to evaluate paper quality without being destructive. Its main advantage is to bring together up-to-date analytical equipment and a non-contact method, which is very appropriate in the case of delicate records of historical interest.

The initial one is sample selection and categorisation. The documents are gathered during the various periods in history, between the 1800s and 2020s, to cover as many types of fibre, additives, degrees of degradation, and modes of production as possible. It has a sample set of both naturally aged and artificially accelerated ones, and it allows the model to be trained on the conditions that are representative of real-life scenarios. The composition and degradation type grouping of samples are important to make meaningful comparisons at later stages of analysis [46].

In spectral data acquisition, the following crucial parameters and characteristics are measured to build the spectral signature database and study paper degradation: spectral ranges reflectance values; absorption features of wavelengths; chemical indicators (e.g. cellulose oxidation, lignin content, pH-related features); colorimetric properties; moisture and fungal activity indicators; and physical surface properties.

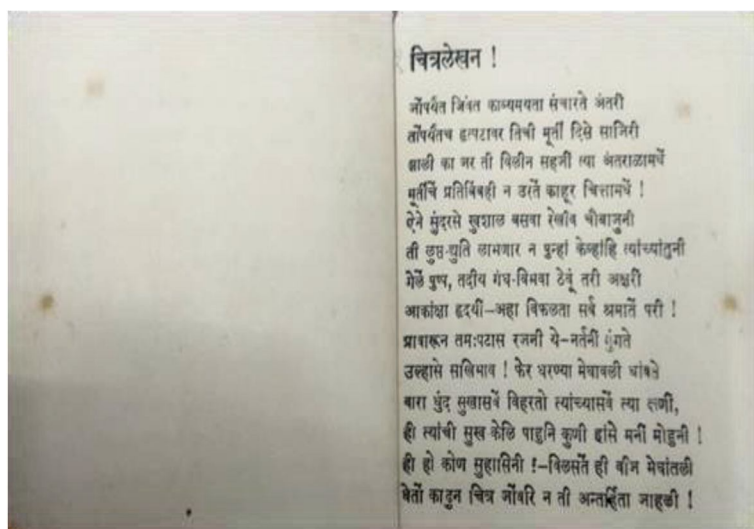


Fig. 2. Sample of Old Paper

The ASD Fieldspec 4 spectroradiometer operates with high resolution reflectance data to collect data in the ultraviolet (UV), visible and infrared (IR) wavelengths between 350 and 2500 nm. This is essential in the detection of chemical changes like acidification, oxidation or fillers and pollutants since various materials react differently to light within this range of the spectrum [50]. After data acquisition, the raw spectral data are subjected to an elaborate preprocessing process to enhance accuracy and consistency. Noisy wavelength bands - usually less than 400 nm and over 2450 nm - are avoided. The effects of environmental noise and instrument variation are minimised by applying baseline corrections, noise filtering, and normalisation [30]. Smoothing filters Savitzky-Golay filters are employed to smooth out random noise without destroying significant spectral characteristics. Any sensor artefacts are eliminated, and any outliers due to abnormal base spikes or shifts are eliminated. There are also detector transition regions between VNIR and SWIR that are carefully treated to avoid spectral distortions.

The next step of feature extraction and analysis is used to determine regularities in the optimized spectral data that are related to certain material properties. Peaks or changes in the absorption at specific wavelengths may be characteristic of cellulose oxidation, yellowing by acids or the use of modern chemical additives. This is the first step towards machine learning classification [50, 45]. The extracted features are then fed into the machine learning algorithms. The high dimensional data is first simplified using the dimensionality reduction methods such as Principal Component Analysis (PCA) and important information is still retained. The samples are then classified models based on the degradation level or material composition. This step converts otherwise a slow, subjective process into a faster, scalable and more consistent process [38, 51].

One of the strengths of the methodology is a built-in validation loop that incorporates objective testing of independent samples together with expert evaluation. This cyclical process will guarantee that the final model is not only statistically valid but also applicable to the practical conservation in a real-world situation. In the end, this framework offers a solid pool of paper quality evaluation and preservation decision-making tools [54, 55].

IV. EXPERIMENTAL SETUP

ASD FieldSpec 4 Analytical Spectral Devices is a high-performance spectroradiometer. It records spectral signature that are indicative of the physical and chemical characteristics of the material being studied. Being one of the most competent tools in the FieldSpec series, it is extensively adopted in the identification, verification, and quantification of materials in various scientific fields. The FieldSpec 4 has three types of detectors with a wide spectral range: the ultraviolet/ visible/near-infrared (UV/ VNIR) region (300-1000 nm), the first short-wave infrared (SWIR1) region (1000-1800 nm) and the second short-wave infrared (SWIR2) region (1800–2500 nm) [56].

TABLE IV: ASD FIELDSPEC 4 SPECTRORADIOMETER SPECIFICATIONS

No.	Parameter	Value
1	Spectral Range	350–2500 nm
2	Sampling Interval	1.4 nm (350–1000 nm); 1.1 nm (1000–2500 nm)
3	Spectral Resolution	3 nm at 700 nm; 10 nm at 1400/2100 nm
4	Scanning Time	100 ms



Fig. 3. ASD FieldSpec 4 Spectrometer Device

Collection of data is based on a standardised measurement. The spectral database is constructed with the help of the RS3 software and the ASD FieldSpec 4 spectroradiometer.



Fig. 4. Spectrometer setup in Laboratory

To achieve the integrity of any spectral signature, laboratory measurements need a controlled dark environment to avoid the interference of the ambient light sources and stray reflections [56].

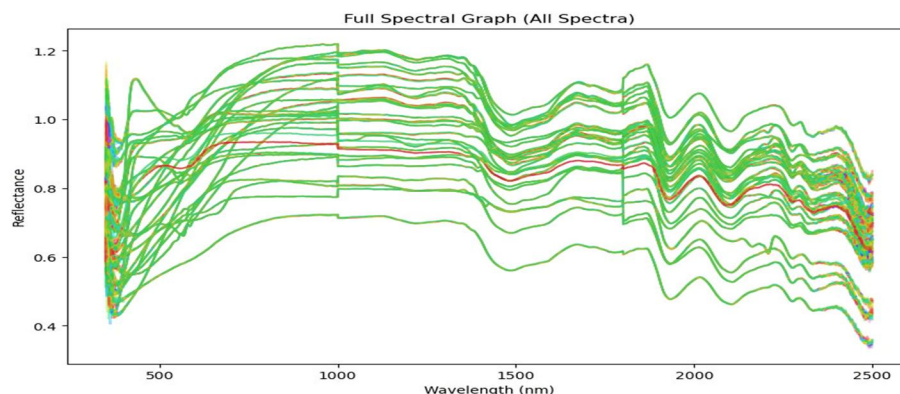


Fig. 5. Raw hyperspectral signature example

The paper includes a review and a suggested methodology. The complete experimental findings, the classification outputs and model performance measures will be published in a follow-up empirical study that is in progress. The spectral signature example shown is illustrative of the type of data produced by the ASD FieldSpec 4 during preliminary measurements.

V. DISCUSSION

The Hyperspectral Non-Imaging Spectroscopy has demonstrated that there are potentially good solutions to analysing paper materials with no damage, but there are a number of outstanding issues. HNIS is useful in identifying chemical changes on the surface of paper, but cannot be used to interpret very localised features like tiny ink spots, small foci of mould or microscopic tears in the fibres of paper. Greater spatial resolution, which can be obtained by combining with HSI, would be especially beneficial in the case of the examination of fragile historical manuscripts.

One of the major constraints is the lack of a standardised spectral reference database. Today, scientists use alternative standards of paper type, additives, and degradation indicators, and cross-study comparisons are not reliable enough and do not allow building machine learning models that need consistently and well-labelled input data. This is known to be an issue in the literature, and one of the most urgent obstacles to the advancement in the sphere.

The HNIS studies do not always include environmental factors, such as humidity, air pollution, and temperature, which have been shown to affect the degradation of paper with time. Real time environmental data would have a significant bearing on the comprehension of how these aspects cause chemical alterations in paper; without this contextual data the predictive capacity of the current models is restricted.

HNIS has applications of machine learning at its early development phase. The vast majority of models have been trained on small, specialised datasets and have not been tested to scale to the diversity of documents contained in libraries and archives. These models require more comprehensive training data and wider testing regimens before they can be confidently put into conservation applications.

By solving these problems, as a group, this would go a long way towards making HNIS a useful tool in preserving paper universally. Advances in fidelity, shared reference data, environmental data integration, and model robustness would essentially alter the management and protection of historical records.

VI. RESEARCH GAPS AND FUTURE SCOPE

A number of obvious guidelines can be drawn out of this review. To start with, the creation of a common open-access spectral reference library of paper materials, comprising of historical samples of various times and production processes, would greatly fasten the pace and be able to compare laboratories. Second, the research of the future should focus more on the combination of real-time or logged environmental measurements (temperature, relative humidity, pollutant levels) and HNIS measurements to construct a more comprehensive degradation model. Third, more extensive and representative training sets, preferably as a collective across institutions, are necessary to create machine learning classifiers with a realistic applicability to museum, library, and archive contexts. Lastly, the integration of HNIS with other complementary imaging methods like HSI or MWIR reflectography needs individual study, where multi-modal sensor fusion could address space resolution limitations of HNIS.

VII. CONCLUSION

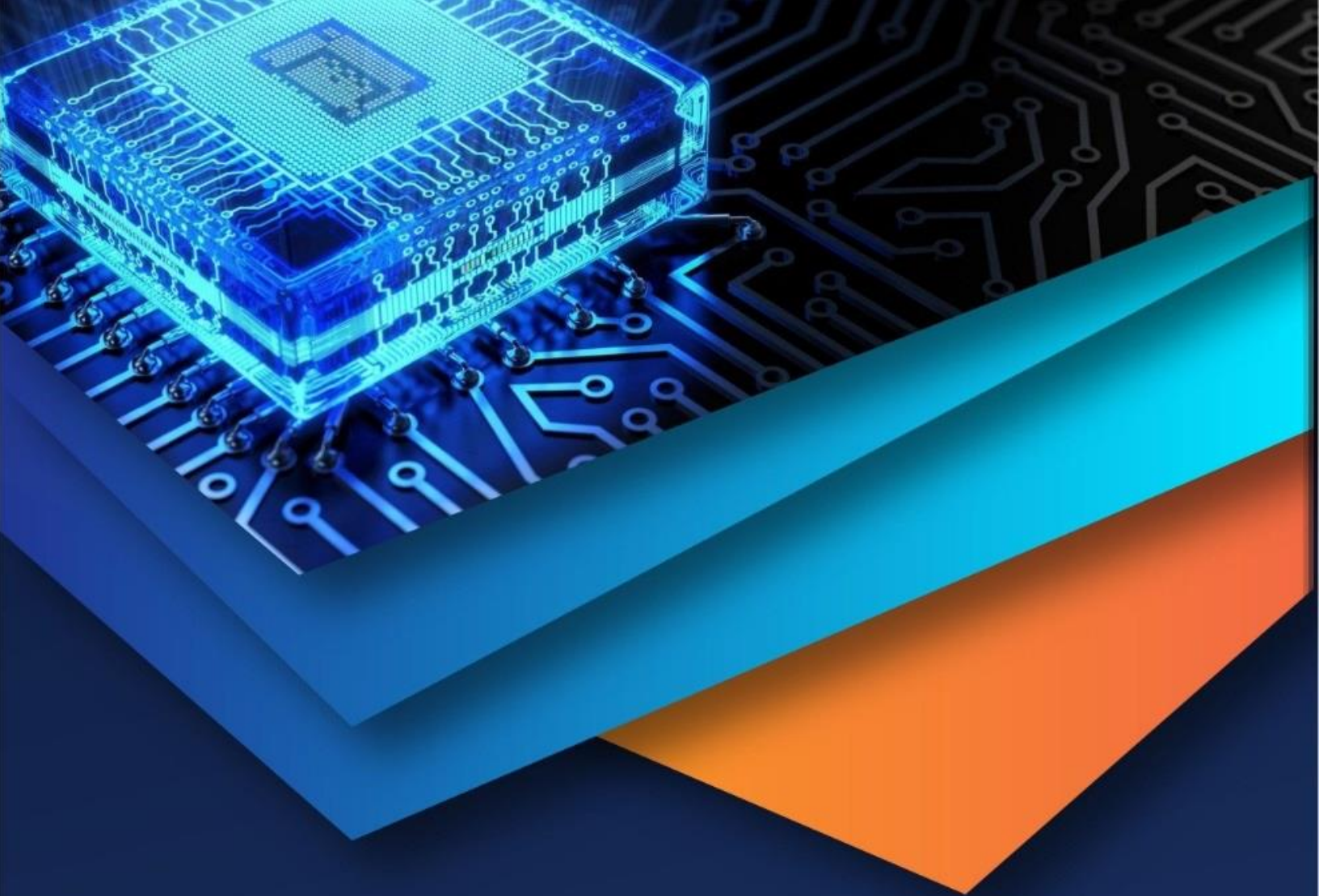
This review has discussed Hyperspectral Non-Imaging Spectroscopy as a non-destructive method of measuring the quality and the state of paper materials such as the rare and historically important documents. The offered methodology, including sample collection and categorisation, spectral data acquisition, preprocessing, feature extraction, machine learning classification, and iterative validation, offers an organised and scalable approach to the assessment of paper degradation under no physical influence. HNIS has shown to be quite appropriate in paper assessment due to ability to identify variations in chemical makeup such as oxidation, acidity and type of fibre by the reaction of paper to light of varying wavelengths. Together with sophisticated methods of data analysis and pattern recognition, these spectral properties allow making an effective classification of paper based on its age and condition, providing conservators with a better foundation to make long-term preservation decisions.

The review also indicates the significance of building a detailed spectral reference database, finding early degradation predictors, and using predictive tools to conserve proactively. Combined with the capabilities enabled by new data analysis methods and the combination of HNIS with machine learning, these capabilities form a basis to further advance the preservation of paper heritage and its protection to the future generations.

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