ASSESSMENT OF RAW PAPERS FROM NON-WOOD FIBRES FOR STORAGE AND PACKAGING OF ARCHIVAL MATERIALS AND CULTURAL HERITAGE OBJECTS THROUGH A MULTI-DISCIPLINARY DIAGNOSTIC METHODOLOGY

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This study aims to propose a multidisciplinary methodology for the assessment of raw papers made of fibres from annual plants, and to investigate their sheet-forming behaviour and potential for packaging materials for cultural heritage objects or archive collections. The study highlights the effects of dry heating artificial ageing on the mechanical and optical properties of the papers. Their morphology was examined through non-destructive spectral imaging in visible (VIS) and ultraviolet-induced visible luminescence (UVL), colourimetry and glossimetry. SEM and Dino Lite handheld digital microscopy have also been employed. The evaluated raw papers presented durability after ageing, with minor changes in pH, visual characteristics (colour/gloss), and mechanical properties (tensile strength), pointing to the usability of non-wood packaging materials. The study can serve as a guide for a multi-faceted diagnostic methodology and *in-situ* testing for the assessment of newly developed and possibly sustainable packaging materials for sensitive archive collections and cultural heritage objects.

Keywords: non-wood fibres, annual plants, green and sustainable packaging, archive collections, cultural heritage, assessment methodology, non-destructive imaging techniques

INTRODUCTION

The global paper market continues to experience remarkable growth, driven by the increasing demand for packaging solutions. Although papers made from wood fibres offer many advantages to the global economy, especially in the field of papermaking and packaging manufacturing, various environmental problems related to climate change are caused by human activity. The most serious one is the degradation of forest ecosystems,[1,2] resulting in biodiversity loss by disrupting ecosystem balance, contributing to the formation of monoculture forests, narrowing the habitats of various plant and animal species.[3,4] Besides, the use of chemical substances and extensive water consumption during paper and board production also affect natural resources, pollute water and deteriorate soil.[5]

Researchers have to solve the problem at the source by the use of alternative, renewable sources of raw materials in the manufacture of environmentally friendly paper and packaging products. In the era where the effects of climate change are omnipresent, the use of non-wood fibres, derived from agricultural residues, annual plants, and recycled fibres with biodegradability properties has gained increasing interest by various industries.[6,7]

Certain advantages of using non-wood materials for the paper packaging industry are mentioned in the literature.[8] For example, non-wood materials, such as bamboo, straw, hemp, *etc.*, have faster growth than wood, and thus, the problem of potential wood scarcity is successfully addressed. Also, paper manufacturing requires less water and energy, showing a much lower environmental impact than in the case of using wood-based materials.[9] However, some issues associated with collection, storage, transportation and handling, as well as some necessary modifications of the existing equipment cause a lack of enthusiasm for the paper industry due to problems of additional costs. Other problems are the high content of nonfibrous materials, such as silica, which must be removed or be separately treated, because they cause difficulties in processing and deteriorate pulp characteristics.[8]

Non-wood fibres are constituted of complex structures based mainly on cellulose. It is an unbranched polysaccharide with a long chain, which is formed by D-glucopyranose units linked by β-(1,4)-glycosidic bonds. Intramolecular and intermolecular hydrogen bonds are formed between the oxygen atoms and the hydroxyl groups of the D-glucopyranose unit, contributing to the crystallinity of cellulose, which is a semicrystalline polymer with a strong hydrophilic character. Cellulose is characterised by unique properties, such as easy availability, renewability, and environmental friendliness.[10]

To our knowledge, although many efforts have been made to replace wood pulp paper with alternatives, to create different types of papers for various applications,[11,12] the related research is still in progress. However, only a few papers made from non-wood fibres have similar characteristics to those from hardwood and softwood fibres. Besides, the characteristics of the new non-wood materials have not been investigated extensively yet, and careful consideration of their formulation is required before their functional use. Specifically, the development of green and sustainable materials for making archival boxes and other packaging systems for the storage or transportation of valuable collections of cultural heritage, ensuring their protection and conservation, is of great concern.[13-17] Academics and professionals from all over the world are facing this challenge, contributing to sustainability in the framework of the 8 Rs (*i.e.* re-evaluate, re-conceptualize, restructure, re-locate, redistribute, reduce, reuse, recycle),[18] based on the rules of 5Rs (reduce, reuse, recycle, rethink and recreate), which are of crucial importance for the field of conservation-restoration.[19] Within the same concept, green methods and materials have been recently developed by several researchers[20-23] for ecological, accessible, sustainable and inclusive processes using environmentally friendly materials without health risks.[24-29]

Cultural heritage items, such as museum objects, archive collections, documents and artworks (paintings, frescoes, archival collections, books, ceramics, stones, *etc.*) are very vulnerable when they are stored or transported for international loans or from one shelf to another in a storage room or area. They require special attention for their conservation and preservation, due to their unique character and fragility, being at risk of damage because of poor handling, fluctuations in environmental conditions, bumps or vibrations. In addition, air pollution, dust, humidity and temperature fluctuations, as well as insects, are some other typical factors that may cause damage, degradation, failure or corrosion of the valuable objects. To protect them, a variety of packaging materials made from paper, cardboard and other materials are being developed, while their selection is based mainly on the type of application. Storage folders, boxes or other containers made from paper and paperboard fulfil the requirements for effective, safe, and affordable materials with enhanced properties, in addition to good mechanical stability and long lifetime, and fully accounting for end-of-life aspects.[30-32] Thus, their use is of great importance for protecting cultural heritage objects from damage and ensuring their long-life conservation.[30,33,34]

However, the physical, chemical, and morphological characteristics of different types of paper, *i.e.* their composition, surface roughness, charge distribution, and porosity, must be carefully considered, as they significantly influence the strength and stability of papers. Paper is a complex material, primarily composed of cellulose, hemicelluloses, lignin, and extractives. The polar hydroxyl (-OH) groups present in cellulose promote hydrogen bonding and contribute to the structural integrity and behaviour of papers.[10,35,36] Thus, ageing and environmental conditions can alter the performance and effectiveness of various paper types when used as protective packaging materials for sensitive cultural heritage objects or other valuable collections.[37–50]

In this research, non-wood papers were prepared from fibres of annual plants to investigate their potential for producing sustainable packaging for cultural heritage objects and archive boxes. For this, a multidisciplinary approach was followed, which combines non-destructive and analytical techniques. The methodology includes the assessment of the mechanical and optical properties of the papers before and after their artificial ageing. The surface morphology of the specimens was examined through non-destructive spectral imaging in visible region and by ultraviolet-induced visible luminescence, as well as by SEM and digital microscopy. The samples were also assessed in terms of colourimetry and glossimetry.

EXPERIMENTAL

Materials

Raw papers were made only from annual plants, *i.e.* flax, hemp, straw and manila (abaca) fibres, and water, on a small lab paper mill. To compare the properties of the pure fibres and resulting papers, no further fillers, additives or sizing were added. These papers were prepared at a research laboratory level to investigate their properties and applicability within the framework of the GREENART project.

Specimens of these papers were cut in accordance with ISO 186, and kept under standard conditions, *i.e.* 23 °C and 50% RH. The grammage of the papers was determined in compliance with ISO 536:2019, and their thickness was measured following ISO 534.

Methods

Artificial ageing

Artificial ageing of papers was carried by dry heating in airtight vessels at 100 °C for 5 days, following ISO 5630-5.

Characterization methodology

pH measurements were carried out on specimens of each type by cold extraction using a Hanna Instrument EDGE pH-HI (2002), following the TAPPI test method T509 om-02.

Colour parameters were measured with the CIE L*a*b* (1976) colour system and reflectance measurements following standard TAPPI T 527 om-02 by using a colorimeter with an integrating sphere (PCE-CSM 10) over a white surface (reflectance more than 89%) as mentioned elsewhere.[51,52] The changes before and after ageing were expressed as ΔE*, which was calculated by the following Equation (1). Three different points of each sample were measured, while for each point three measurements were considered to calculate the average values of ΔE*.

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (1)$$

Surface gloss measurements of specimens were carried out using a TG 60/268 Lovibond gloss meter and GQC6 Quality Control Software (ISO 7668) was used to determine the intensity of light reflected at three measurement angles of 20°, 60° and 85°.[53]

The mechanical behaviour of the papers was investigated with tensile strength measurements. Paper specimens with dimensions of 2.5 x 10 cm were tested using an Instron 3400 testing system (TAPPI test method T494). Specimens were kept for 24 h under room conditions of 23 °C and 50% RH, and the measurements were carried out under the same conditions. Ten measurements were obtained for each specimen, five for each principal direction of the paper, *i.e.* machine direction (MD) and cross direction (CD) respectively.[51,52,54,55]

Morphological changes of the papers were evaluated by Scanning Electron Microscopy (SEM), using a JEOL JSM-6510 LV-EDAX (Oxford Instruments) equipped with Energy Dispersive Spectroscopy (EDS). The changes after accelerated ageing were recorded for the different types of papers.

Evaluation was also carried out with a Dino Lite handheld digital microscope in two spectral regions (visible and UV).[56] The morphological changes of the specimens were recorded using a Nikon D800 digital single lens reflex camera (DSLR), equipped with an AF-S Nikkor 24-70mm 1:2.8G ED lens. A stand was employed to support the paper samples. For VIS imaging, two J78 halogen lamps were used for symmetrical illumination. For the UVL imaging, one LED UV source with emission at 365 nm was used for excitation radiation. A Kodak 2E barrier filter was used to balance excess blue radiation from the light source. The samples were photographed with an X-Rite Colorchecker© colour and metric scale. The procedure was carried out in complete darkness.

RESULTS AND DISCUSSION

pH changes

The grammage and the thickness of the prepared papers were determined and the results are presented in Figure 1.

The changes in pH values of the papers were examined before (BA) and after (AA) accelerated ageing and are presented in Figure 2. All samples showed slightly alkaline pH values before ageing, and became neutral or slightly acidic after ageing, confirming observations mentioned in the literature, *i.e.* changes to slightly acidic values after ageing of papers.[42] The greatest change was observed in straw paper (*i.e.* 9.6%) and the lowest in the papers from flax (*i.e.* 4%). The results indicate the chemical stability of the examined papers even after dry heating, confirming the stability of glycosidic bonds of cellulose, as happens in alkaline and neutral environments. In contrast, more acidic values could be indicative of the failure of the paper’s strength, probably due to the acceleration of the hydrolytic failure of the glycosidic linkage.[42] However, the higher amount of lignin content in manila paper, which contains at least twice the percentage content of lignin in flax and hemp fibres,[1] does not appear to cause a considerable impact on the variation of pH, which was found to be 5.4%, a fact also observed by other researchers.[42]

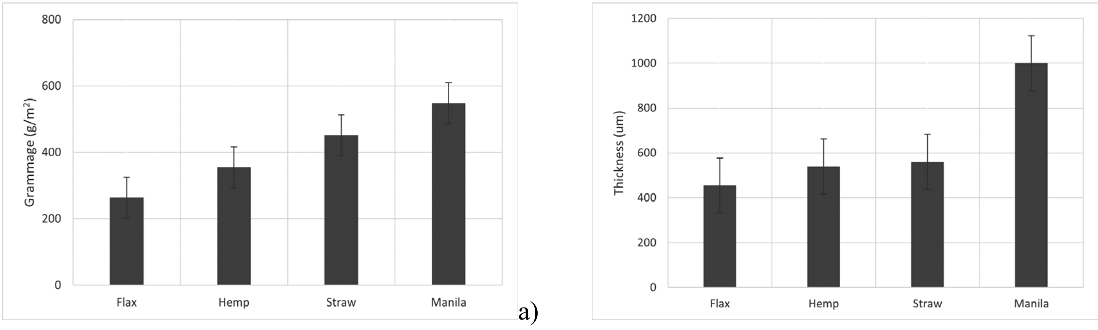

Figure 1: Grammage (a) and thickness (b) of the prepared non-wood papers

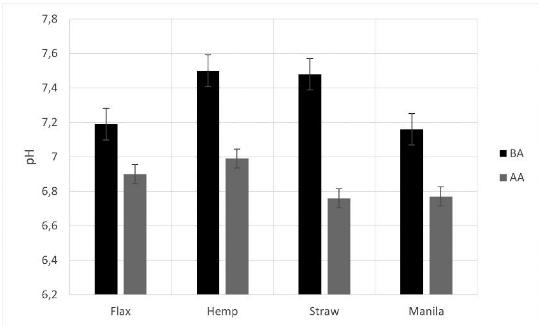

Figure 2: pH values of papers measured before (BA) and after (AA) artificial ageing

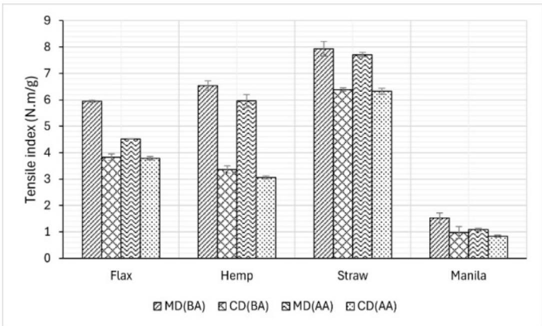

Figure 3: Tensile index of non-wood papers in machine direction (MD) and cross direction (CD), before (BA) and after ageing (AA)

Tensile strength changes

Tensile strength measurements of the examined paper specimens were performed to further investigate their mechanical behaviour and thus their potential capability to be used as packaging materials. These measurements were carried out at different orientations of papers related to the fibre alignment, *i.e.* parallel or cross-grain direction, MD and CD respectively, following the TAPPI standard for tensile strength (T494). Thereafter, the values of tensile index were calculated using Equation (2):

Tensile index = tensile strength/grammage, quoted in Nm/g (2)

The results were summarized and presented in Figure 3. The measured values of tensile index (Fig. 3) show very low standard deviation, indicating high consistency. The tensile index values measured in the machine direction (MD) of papers were much higher – by 1.2-1.9 times – than those taken in cross direction (CD); these results agree with previous literature,[54] where a variation by a factor of approximately two between MD and CD is mentioned. In the present research, the differences in the values refer to the effects of ageing.

Changes in the tensile index after ageing of the various types of papers examined in this study are indicative of their degradation. It was found that the extent of these changes depends on the type of paper and on their orientation during the testing (*i.e.* MD and CD). The decrease in tensile index values in MD after ageing is approximately 3.0% for straw paper, 8.5% for hemp paper and 24% for flax paper. The alterations in tensile index in CD of papers from flax and straw after ageing are negligible, while for hemp paper, a change of about 10% was calculated. Manila paper exhibits low tensile strength (Fig. 3) even before ageing, and this fact is in line with the results referred to in the literature.[1] In addition, it was observed that the samples of manila became a little stiffer after ageing, showing a decrease in tensile index values of approximately 30% in MD and 15% in CD, revealing a high degree of deterioration because of ageing. This observation is correlated to other researchers' findings, who mention that the low flexibility of rigid papers affects negatively the fibre strength properties.[54-58] However, it could be assumed that if a paper made from manila fibres is properly treated, it could achieve consistent, acceptable quality and thus offer significant value to packaging manufacturers by simultaneously reducing the cost of their production.[59]

The aforementioned results are consistent with generally accepted knowledge regarding the evolution of the tensile strength of paper after ageing. A strong dependence of the tensile strength behaviour on the type of fibre, the extent of crystallinity, and the type of molecular interactions between polymeric cellulose chains has been reported.[54] The polymeric macromolecule of cellulose has three hydroxyl groups per anhydroglucose unit in the chain, which can lead to strong intermolecular interactions via hydrogen bonding.[54,60] Thus, when paper undergoes ageing, changes in crystallinity of cellulose may occur, which reflect alterations and degradation in hydrogen bonding, inter- and intra-fibre bonds cleavage, oligomer fragment formation, production of shortened and less bonded fibres, and increased brittleness.[61-63] Moreover, since aged paper loses water by dry-heating, which works as plasticizer by forming intermolecular H-bonds with cellulose, it consequently loses its flexibility, and its mechanical strength becomes lower.[42,64-69] These phenomena cause depolymerization of paper-based materials, affect significantly their mechanical strength and lead to paper degradation. The elucidation and control of the factors that influence the properties of non-wood papers after thermal ageing are of great concern. Thus, the present study aims to bring a contribution in the area of sustainable non-wood paper-based packaging materials, which is of interest to papermakers and conservators.

Moreover, the changes remarked in the present study in tensile strength after ageing of the papers are consistent with the alterations in pH values discussed above and also correlate with the colorimetric parameters (*i.e.* ΔL^* and ΔE^*) analyzed in the following sections. These findings agree with those reported by other researchers,[70-72] who mention that the type and composition of fibres, their structure and bonding, as well as the papermaking techniques, such as the method of production and the drying process in paper manufacturing, are principally responsible for the mechanical strength of papers.[62,73] It can be concluded that the examined papers exhibited good stability and structural integrity and could be used as protective packaging materials for archival collections.

Imaging techniques

The samples were photographed in collectively and are presented in Figure 4. Images of the samples subjected to mechanical tensile strength experiments, before (BA) (rows 1, 3 in Fig. 4) and after (AA) (rows 2, 4 in Fig. 4) artificial ageing, for machine direction (MD) (rows 1, 2 in Fig. 4) and cross direction (CD) (rows 3, 4 in Fig. 4), show details about the failure and the appearance of the specimens.[56,74]

Images were taken under symmetrical illumination in the visible spectrum (Fig. 4), to record the colour of the samples. Flax, hemp and straw presented only slight changes in their colour, but manila samples presented a shift towards a yellowish hue after ageing.

Raking illumination was used in order to record the tear and distortion, which the tensile strength experiment caused to each material (Fig. 4). Most of the samples examined, *i.e.* flax, hemp and straw, presented a tear, flax and hemp papers showing long untorn fibres, while the straw paper showed a complete scission of its fibres during the testing (Fig. 4). The details of the fibres visible at various tearing sites are helpful to better understand the resistance of each type of paper and its behaviour depending on the type of fibre contained. Manila paper samples were not torn, rather slightly disfigured and elongated, showing some wrinkles and creases. They presented different extents of distortion, depending on the direction of the paper cut, *i.e.* more distortion in machine direction and less in cross direction.

Ultraviolet-induced visible luminescence was also used to analyze the samples (Fig. 4). Flax, hemp and straw present a minor fluorescence change after the artificial ageing, indicating that the degradation of cellulose had been initiated.[74] Manila paper presents both more intense fluorescence and a change in the fluorescence colour, which, in combination with the change in colour in the visible spectrum, indicates that the artificial ageing has caused more extended degradation.

The Dino Lite handheld digital microscope shows the characteristics of the fibres at the points where the paper broke during the tensile strength testing (Fig. 5). Flax and hemp present long, undisrupted fibres, while the straw paper shows different behaviour because its fibres appear sharply broken. UVL microscopy of the samples confirms the absence of optical brighteners or other additives in the paper. It also depicts more clearly the structure of each paper. Especially in the case of manila paper, the distortions are evident (Fig. 5).

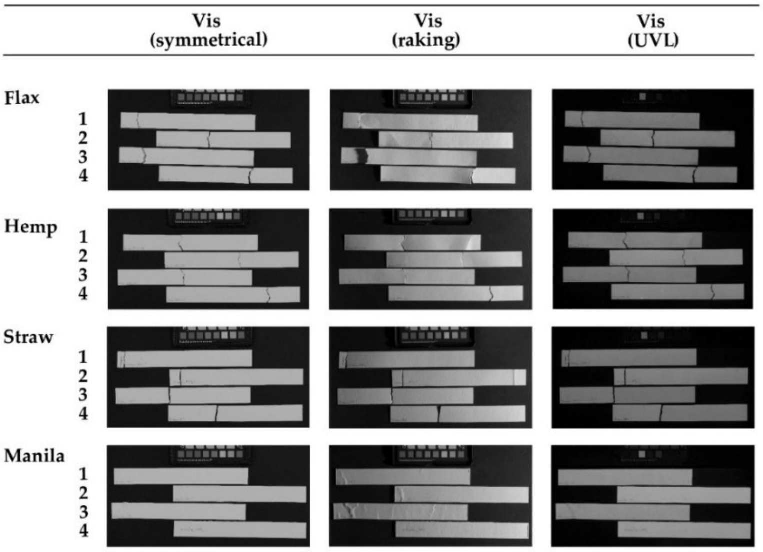

Figure 4: Images of flax, hemp, straw and manila samples, in visible symmetrical and raking illumination, as well as in ultraviolet induced visible fluorescence mode. The numbers stand for: (1) MD before ageing, (2) MD after ageing, (3) CD before ageing and (4) CD after ageing

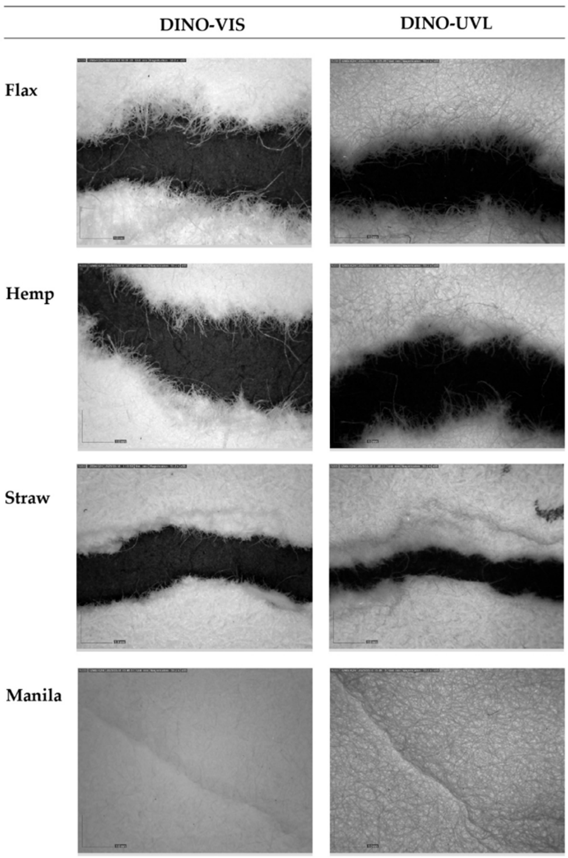

Figure 5: Images of flax, hemp, straw and manila samples, at 50x (Dino Lite) under visible and ultraviolet illumination after the mechanical tensile strength experiment

Colour and gloss changes

The initial description of the paper colour, before ageing, is provided by the colourimetric parameters L*, a*, and b*, which were obtained spectrophotometrically and are shown in Figure 6. The values of brightness (L) of all the samples are very high, of about 95 (Fig. 6), the values of a* are close to zero (*i.e.* ranging from -0.4 to -0.5 representing green), while the values of b* are very low (*i.e.* ranging from 4.2 to 5.8 representing yellow) due to the yellowish appearance of the papers.[51,52]

To determine the colour changes observed in the papers after ageing, the analysis focuses on the variations in % reflectance spectra of the samples, as illustrated in Figure 7. Slight differences are detected in all cases, especially in the range of 400-550 nm. The most noticeable changes are observed mainly in the case of the aged Manila paper (Fig. 7), as has already been recorded by imaging techniques.

A more detailed characterisation of the colour changes in the papers after ageing is provided by the differences in the colourimetric parameters (ΔL^*, Δa^*, and Δb^*) between the values obtained before and after ageing of the samples, as shown in Figure 8. Changes in the values of brightness (ΔL) are observed in the case of Manila paper, implying a slightly darker colour of the aged papers. However, smaller changes are detected in the hemp and straw papers, while the values obtained for the flax paper remained almost unchanged (Fig. 8). The variations in Δa^* values, which show the red/green differences, are insignificant for all the papers examined (Fig. 8).

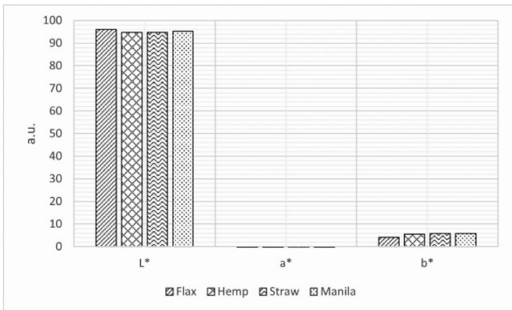

Figure 6: Colour coordinates of the papers examined before ageing

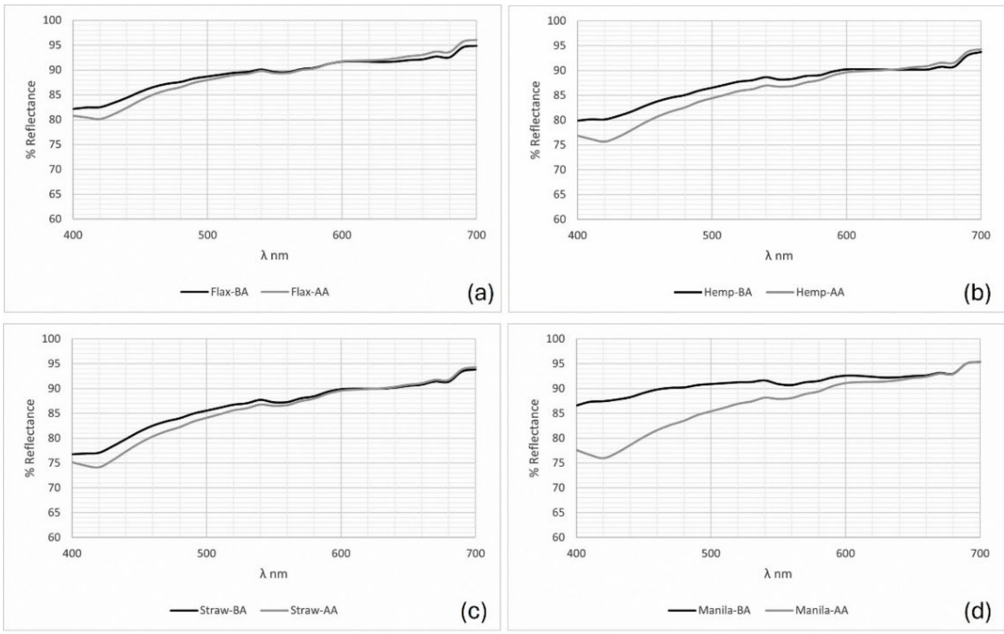

Figure 7: % Reflectance of specimens measured before (BA) and after ageing (AA)

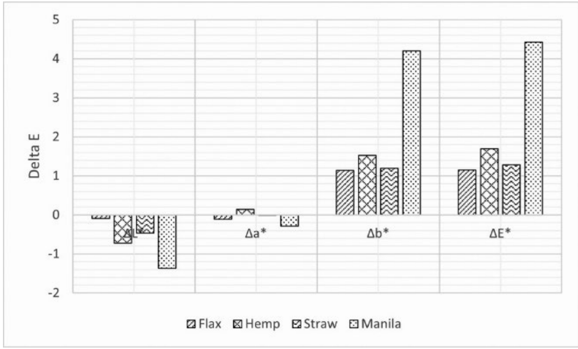

Figure 8: Delta E values of colour coordinates of examined papers measured before and after ageing

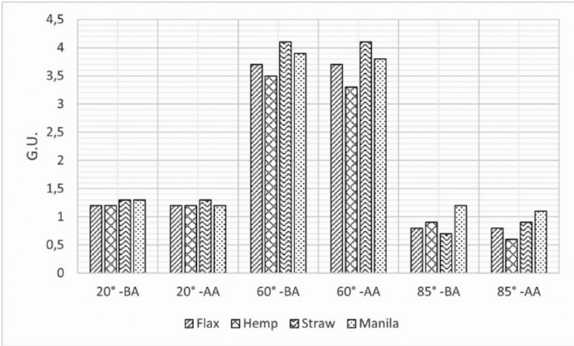

Figure 9: Gloss of examined papers before (BA) and after (AA) ageing

In the same figure, manila paper presents a noticeable increase in Δb*, showing a shift towards yellowness (Fig. 8). The other three types of paper exhibit small changes, which are detectable spectrophotometrically, ranging from 1.1 to 1.5 in these two parameters. Similarly, very small alterations are observed in ΔE* values ranging from 1.1 to 1.7 for these three papers, which are not detectable by the naked eye. However, the change for Manila paper is more intense and visible even to the naked eye: ΔE* = 4.44 (Fig. 8). These differences are probably caused by the lignin contained in the paper, even in very low amounts, as has been confirmed in other studies in related literature.[1]

As glossiness represents the condition of the surface of the papers (*i.e.* smoothness and softness), it can be used to offer information about the status of the surface and the stability of the materials,[53] as well as about the potential alterations caused by artificial ageing. Thus, to assess the impact of dry heating on the visual appearance of the papers, their glossiness was also measured, and the results obtained are presented in Figure 9. As may be noted, the values of the glossiness for all the papers before ageing were very low. This was expected, since the examined papers were uncoated, and without any additional surface treatment. The glossiness measurements were carried out at different angles to describe in detail any differences after ageing of the papers. It was found that the glossiness values were much higher at 60° than at 85° and 20°.

When the gloss measurements on the aged papers were carried out at 20°, the changes were obvious only on manila paper (*i.e.* 7.7%), while at 60° changes were observed both on hemp (5.7%) and manila paper (2.6%). The effects of ageing on glossiness were most visible when the measurements were carried out at 85° (*i.e.* 8.3% for manila, 28.6% for straw and 33.3% hemp). It is worth noticing that no changes in glossiness were observed on flax paper, which shows excellent stability.

It could be concluded that, in the present study, the measurements of glossiness revealed almost negligible differences after ageing, since the papers have a quite matt appearance. These differences could be attributed mainly to the degree of dehydration of the samples after their ageing. However, the effects of different characteristics of the fibres (diameter, thickness, which influence the roughness of the paper and thus glossiness) or the paper-making process in the small laboratory machine that was used in the present case could be further investigated.

In conclusion, the insignificant alterations in the optical properties of the hemp, straw and flax papers indicate their good stability, durability and integrity. Thus, the assessed papers are expected to be suitable as packaging materials to protect sensitive archival collections or museum objects. However, a more detailed analysis and treatment of manila paper should be done before its use for this purpose.

Morphological analysis

The morphological analysis of the specimens was carried out through scanning electron microscopy (SEM) and the micrographs are presented in Figure 10. Insignificant (negligible) differences are observed in SEM representative micrographs after ageing of the samples, indicating that the examined papers are durable, and their morphology as well as their structure have not been affected considerably by the ageing process.

As seen in Figure 10, papers made from flax and hemp contain non-uniform fibres, which vary in diameter from wide to narrow having pointy ends. The fibres are long and thin (slender), with an average width of about 15 μm. These observations agree with the results of other researchers, who found that flax fibres have a fibre length of 1.41 mm, with a diameter of 16.78 μm, lumen width of 9.45 μm, and cell wall thickness of 3.77 μm.[8,75] Occasionally, thicker ones, with diameters of 25 μm and 45 μm are noted in Figure 10. The randomly oriented fibres create a non-uniform network, with a highly interconnected structure. Some voids are observed (especially after dry heating, probably caused by dehydration), which were unevenly distributed. As mentioned by other researchers,[1] this type of morphology and the low lignin content in these fibres could facilitate paper-making, resulting in a faster pulping process with the use of less harmful chemicals. The length of flax, hemp and straw fibres and the compactness of the pulp can also explain the high mechanical strength discussed earlier in the study, as also reported in other published works.[75]

Paper made from straw exhibits a uniform structure, with wider fibres than those in flax and hemp, having a diameter of at least 15-25 μm (Fig. 10), while the network is denser than in the case of flax and hemp, without large voids. Straw fibres are thick-walled with cell walls determined to be of about 3.5 μm (Fig. 10). These results agree with the findings of other researchers, who mentioned an average length of 1.4 mm (0.4-3.2 mm) and a width of 0.015 mm (0.08-0.034 mm).[76] Other studies demonstrated that this straw based paper has high density, and exhibits high mechanical strength and softness.[36]

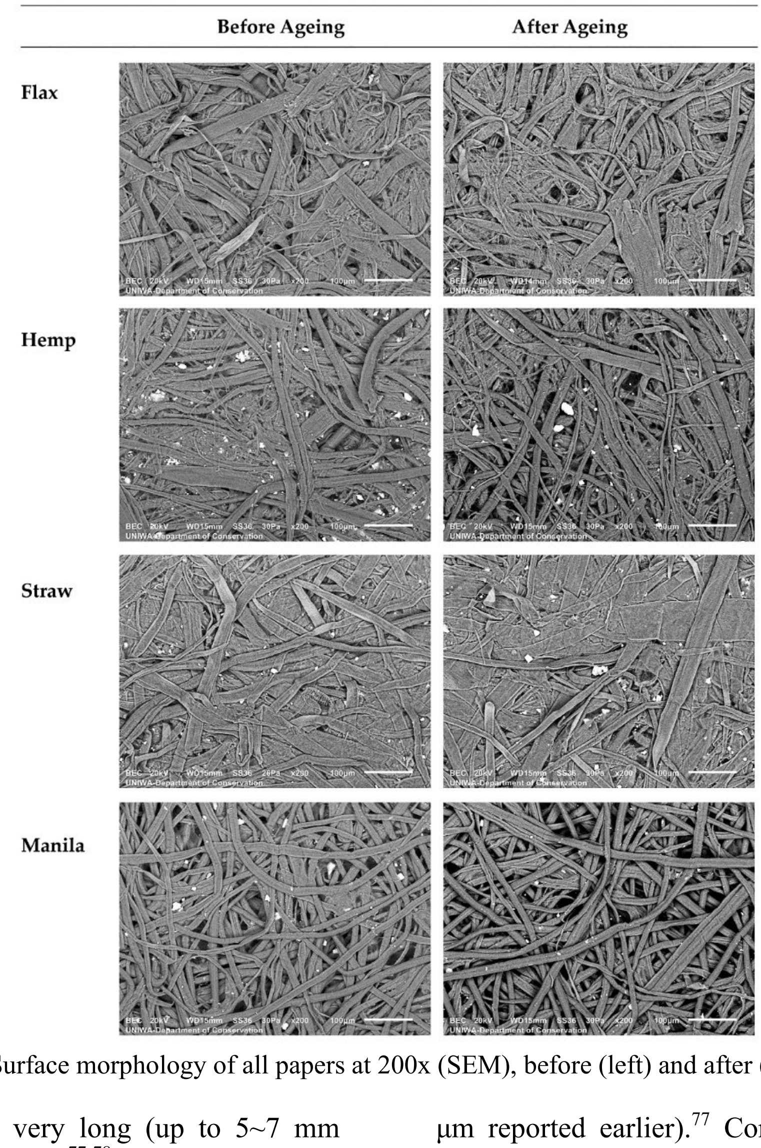

Figure 10: Surface morphology of all papers at 200x (SEM), before (left) and after (right) ageing

Manila fibres are very long (up to 5~7 mm according to the literature)[77-78] and thick, with an average fibre diameter of about 10-15 μm (20-24 μm reported earlier).[77] Commercial grade abaca has been measured to show an average fibre length of 6.0 mm,[79] 4.4 mm,[80] and 3.15-5.45 mm.[81] The length of fibres obtained from manila plant wastes was characterised as medium to extremely long (0.92-7.73 mm), with a cell wall thickness of 2.0-8.0 µm. The long fibres contribute to a relatively uniform network, leading to a bulky paper with weak mechanical properties. This probably explains the fact that the specimens of manila paper in this study did not break at the point of failure during the tensile strength test, but rather only elongated. Although this type of morphology results in increased softness and porosity, other researchers mention that the very long fibres and high thickness cause problems during the papermaking process.[76]

After ageing, only slight signs of failure (degradation), such as defects, brittleness, rupture and decay, were detected (Fig. 10), verifying the sufficient stability and durability of the examined papers. These results show the potentially advantageous use of these papers for packaging application.

CONCLUSION

This study evidences the assessment of non-wood fibres, as potential raw materials for packaging for archival collections or cultural heritage objects. The mechanical and optical changes of papers made from annual plants (flax, hemp, straw and manila) were investigated before and after their artificial ageing. It was found that the examined papers made from flax, hemp, straw fibres and water only, without other additives, exhibited sufficient stability and structural integrity, ensuring the capability to be used as protective packaging materials for archive collections. Manila paper would require a proper surface treatment to ensure its applicability in the field of papermaking and packaging.

The morphology of the specimens was also evaluated through non-destructive spectral imaging in the visible and near infrared regions, by ultraviolet-induced visible luminescence, colourimetry, glossimetry, as well as microscopy techniques, such as SEM and digital microscopy. After ageing, the examined raw papers made from flax, hemp and straw fibres showed slight variations in appearance (colour and gloss), similarly to insignificant changes in pH and mechanical strength (tensile strength). Considering their stability after artificial ageing, it could be presumed that by adding typical fillers additives, the desired properties can be further adjusted. Therefore, the prepared papers can be considered promising for being applied as packaging materials for protecting valuable archive collections.

The results obtained in the present study provide a better understanding of the optical and mechanical properties of the examined papers, highlighting the importance of using non-wood fibre papers by the packaging and printing industry for a more sustainable future. Also, a multi-faceted diagnostic methodology is an important tool for the assessment of newly developed green and sustainable packaging materials for sensitive archive collections and cultural heritage objects, combining common mechanical (destructive) and non-destructive techniques.

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