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Bast from the past: the fibre architectures and properties of Ancient Egyptian and Peruvian fishing nets

Alain Bourmaud¹ , Camille Goudenhooff¹, Camila Alday Mamani², Sylvie Durand³, Alessia Melelli⁴, Loren Morgillo¹, Mario Scheel⁴, Michel Ramonda⁵, Timm Weitkamp⁴, Roberta Cortopassi⁶, Frédéric Jamme⁴, Johnny Beaugrand³, Olivier Arnould⁵, Anita Quiles⁷, David Beresford-Jones², Darshil U. Shah^{8,a}

¹ IRDL, UMR CNRS 6027, Univ. Bretagne Sud, Lorient, France

² McDonald Institute for Archaeological Research, University of Cambridge, Downing St, Cambridge CB2 3ER, UK

³ UR1268 BIA Biopolymères Interactions Assemblages, INRAE, 44316 Nantes, France

⁴ Synchrotron SOLEIL, 91190 Saint-Aubin, France

⁵ UMR CNRS 5508, LMGC, Université de Montpellier, Montpellier, France

⁶ Département des Antiquités Égyptiennes, Musée du Louvre, 75058 Paris, cedex 1, France

⁷ Institut Français d'Archéologie Orientale du Caire, Le Caire, Egypt

⁸ Department of Architecture, Centre for Natural Material Innovation, University of Cambridge, Cambridge CB2 1PX, UK

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Abstract Bast fibres have been critical materials in the evolution of human history. In particular, their use in fishing technology as well as in maritime transport has enabled mobility, livelihoods, and the exchange of goods and transmission of cultures in human societies. Here, we compare fishing nets from two distant but contemporaneous groups at the end of the 4th millennium BCE: one from Neolithic period in Egypt and the other from the Middle Preceramic Peruvian Pacific coast. The fishing nets possess substantially similar textile architectures even though they use bast fibres from different species: domesticated cf. *Linum usitatissimum* L. (flax linen) by the Ancient Egyptians and cf. *Asclepias*. (milkweed) by the coastal Peruvian community. We examine these two fibre types and show that despite their distinct morphological and ultrastructural characteristics, their processing and manufacture share some similarities, both 2-ply with Z final torsion. Multiphoton, atomic force, and scanning electron microscopy are supplemented by 3D micro-computed X-ray phase-contrast tomography to investigate the unique architectures of the yarns and their fibres' artefacts. We demonstrate the use of state-of-the-art micro-spectroscopy techniques for archaeobotanical studies and use fishing nets as a new lens to unravel the *episteme* and *techné* of fibre and textile production in the past.

1 Introduction

Plant fibre technologies have long contributed to the development of human societies. Thousands of varieties of plant fibres from different plant organs have been used according to their local availability, ease of extraction, and quality and performance amongst other things. Flax (*Linum usitatissimum* L), for instance, was domesticated between 10,950 and 4000 years ago [1–4] by the civilizations of the Fertile Crescent, the earliest indication of domestication ascertained through fragments of capsule found in Jericho (10,250–9000 BP) [5]. Flax (wild and domesticated) was also the main fibre used in Egypt [6], and examples of linen sails have been discovered [7, 8] which may have been reused for smaller sails or mummy wraps [6]. Flax has been one of the strongest plant fibres available for millennia. More recently, and particularly between the 16th and the eighteenth century, the production and trade of flax fibres led to substantial economic and industrial development of Northwest Europe, such as in Flanders [9].

Direct evidence of plant fibres, probably from trees, has been discovered in French lakeside regions, dating back to the Neanderthal period [10], for use in rope-making. Artefacts made from plant fibres were also commonly used to waterproof the hulls of ships [11]. Such practices were widespread between the 6th BCE and 2nd CE centuries and required very large quantities of fibres, flax being particularly popular. For example, the waterproofing of the Gyptis, a 6th-century Greek sewn fishing boat, was completed with 5 km of flax thread, requiring more than 3000 h of weaving [12]. Greece made a major contribution to the development of the use of plant fibres in the nautical industry with the huge expansion of its fleet from the eighth century BCE, both for reasons of economic expansion and for military conquests [13].

On the Pacific coast of South America, civilization itself may have been founded on the exploitation of rich marine resources during the Late Preceramic period in the 3rd millennium BCE [14, 15]. These marine resources were—and still are today [16]—harvested using sophisticated fishing gear, including hooks and lines, and a variety of nets from specifically selected plant fibres according to

^a e-mail: dus20@cam.ac.uk (corresponding author)

the size or behaviour of fish [14]. Among the fibres with suitable properties of fineness and length for splicing (hand technology for manufacturing threads, by assembling fibres or bundles, without specific tool), those derived from gathered wild cf. *Asclepias*. (milkweed) stems were widely used in the Americas [14, 17]. Previous studies have identified cf. *Asclepias* in our study area (Beresford-Jones et al. 2018), the only true bast fibre-producing plant documented in South America. In contrast, other regional fibre sources—including rushes, sedges, cattails, tillandsias, and agaves—originate from soft leaves and stems rather than true bast fibres, which are primarily used for other plant-based artefacts. Based on these considerations, we propose that our samples do not derive from cotton but rather from a bast fibre. Milkweed fibres have suitable physical and mechanical properties for fishing gear, with higher breaking and tensile strength than cotton [18]. To date, no cotton seeds or fibres have been found in our study area for the Middle Preceramic period. As a textile plant, cotton (*Gossypium barbadense*) did not become widespread along the Pacific coast until the Late Preceramic period (after 5000 BP) [19, 20].

Precise identification of plant fibres is always challenging; ancient plant fibres could be visually similar [21] and most of the time difficult to differentiate. Nevertheless, reliable identification in archaeology is preponderant on linking research work with historic use and textile processing. Kallenbach proposed a detailed method for *Linum lewisii*, *Urtica Dioica*, and *Asclepias* fibres identification [22], with the protocol being mainly based on cellulose twist (Z or S), morphology of fibres, and also colour and density of defects such as kink-bands (also called dislocations) [23, 24]. These morphological defects are generally induced by mechanical extraction [25, 26] and characterized by both misalignment of cellulose (with high microfibrillar angle reaching 30–40°) and significant pores concentrically organized around the lumen [27, 28]. In case of doubt in identification, additional experiments such as by scanning electron microscopy (SEM) or polarized light microscopy (PLM) could be performed. The combined use of SEM and PLM is also underlined by Lukesova and Holst [29], who propose a simplified method for fibre identification, and that the research community moderates the affirmations when a secure identification is not possible.

Over time, plant bast fibres were largely supplanted by cotton, especially for textile application, which was domesticated independently in both Eurasia or Africa and Americas for reasons of ease of processing [14] and higher yields [18]. Indeed, the extraction of fibres from bast plants, such as flax and milkweed, can be more difficult because of the better cohesion of tissues [30]. The widespread adoption of cotton has also been largely driven by its economic competitiveness, made possible by lower production costs, the availability of cheap labour and its integration into well-established international trade networks [30]

Across time, seafaring and fishing have been economic sectors heavily reliant on the use of bast fibres. Ancient objects linked to fishing can be found in many parts of the world. Figure 1 illustrates the importance of fishing in pre-historic times, with a panel illustration (Fig. 1.C, Saqqarah, Egypt) depicting a fishing scene and, in particular, a net, possibly made from flax fibres. A net from Ancient Egypt is on display at the Louvre Museum (Fig. 1.A), and the collections of the Cairo Museum contain many artefacts used for fishing, such as harpoons and spears (Fig. 1.E, G) or net weights (Fig. 1.G). All these items bear witness to the importance of fishing, an activity that was fundamental to the diversification of the food supply. Likewise, fishing implements form parts of museum collections along the Pacific coast of South America and are excavated from sites dating back to the Preceramic Period including at La Yerba II and III sites where hooks (Fig. 1.B), net-making needles (Fig. 1.D) and fragments of lines and nets (Fig. 1.F) have been found [14].

In the context of this work, two samples from ancient fishing nets were studied: one from the flax (*Linum usitatissimum* L.) fragment from the Egyptian Antiquities Department Collection of The Louvre Museum (Fig. 1.A) and the other of milkweed (cf. *Asclepias*.) excavated from the Middle Preceramic site of La Yerba III on the south coast of Peru (Fig. 1.F). Structural analyses using multiphoton and electron microscopy were supplemented by microtomography using synchrotron radiation. The local mechanical performance of the cell walls was investigated through atomic force microscopy in Peakforce Quantitative Nanoscale Mechanical (AFM-PF QNM) characterization mode. Applying such cutting-edge techniques to historic plant fibres from the two samples, we study the morphological, structural, and age-related qualities of two diverse bast fibre groups (flax and milkweed). This helps us understand the know-how and craft skills of fibre production in the past, and assess how fibre damage mechanisms may progress over time in these two families of plant cell walls.

2 Materials and methods

2.1 Materials

Two samples of plant fibre yarns were studied: a small yarn extracted from an ancient Egyptian fishing net, conserved in Le Louvre Museum (Fig. 1.A), and a part of a Peruvian fishing net, made from cf. *Asclepias* fibres and found in La Yerba III archeological site [14] (Fig. 1.F).

Regarding the Egyptian object from the Louvre Museum (E 286), this object entered the museum in 1852 from a collector (Clot bey C 22 nos. 155 and 156), unfortunately every other archaeological context information has been lost.

Regarding the Peruvian sample, the fragment was excavated from SU (stratigraphic unit) 9756, Trench 2 in our 2015 field season at the village of La Yerba III, on the Rio Ica estuary, south coast Peru (the precise location of Trench 2 is UTM WGS 1984 18L: 440,012.2000 E, 8,357,032.2900 N, surface at 29.4 m amsl). Trench 2 was a cut through midden (rubbish) deposits alongside houses at the edge of the ancient village.

Fig. 1 A non-exhaustive panel of uses of plant fibres and specific tools for fishing activities by Ancient Egyptians (A, C, E, G) and Peruvians (B, D, F): Fishing nets from Egypt (A) and La Yerba III, Peru (F), Cactus spine fishing hooks (B), Fishing scene on bas-relief in Saqqarah, Egypt (C), Net making needles (D), Spears and harpoons, (E, G), and Fishing weights (G). Images A, C, E, F, and G come from the personal authors collection, they were taken on site at Le Louvre Museum (A, origin unknown), Saqqarah, Egypt (C), at the Egyptian museum, Cairo, Egypt (E, G, origin unknown) and B, D come from [14]. A and F are the samples studied in this paper and described in materials and methods section



La Yerba III is an example of one of the first settled villages that were established along the coast of Peru around 6000 BP. Other examples are at Paloma, Chilca I, Paracas, Santa Ana [31–33]. These villages are significant because they represent the earliest evidence of settled lifestyles, some agriculture, and complexity in coastal communities.

More information about the Peruvian archaeological site and samples is available in [34].

The two samples were radiocarbon dated in 2023 (Laboratoire de Mesure du Carbone 14, SacA70167, CEA-Saclay, Gif-sur-Yvette, France): flax and likely milkweed plants have been dated, respectively, at 5350 ± 30 BP (between 4324 and 4053 calBCE) and 5265 ± 30 BP (between 4230 and 3986 calBCE) (probability 95.4%). In addition, a contemporary flax ribbon was used. It was produced from a mix of textile flax cultivated in 2022 in Normandy (France) by Teillage Saint-Martin company; this flax was dew-retted over 6 weeks and then scutched and hackled.

2.2 SEM observations

For each of the two yarns and modern reference, a sample of a few mm length was used. A Jeol JSM 6460LV scanning electron microscope was used to analyse the flax yarns; secondary emission electrons were used, and the accelerating voltage was 3.0 kV. Complementary analyses were conducted using a TableTop SEM Hitachi TM3030 at the McDonald Institute, University of Cambridge. The yarn samples were then glued to a sample holder using a conductive adhesive and then metallized with a thin layer of gold using an Edwards Scancoat Six device for 180 s.

2.3 Polarized light microscopy observations

Polarized Light Microscopy (PLM) has been used with a Leica DM4000, in dark-field mode) to explore possible dislocations in ancient Peruvian fibres.

2.4 Multiphoton microscopy

2.4.1 Preparation of samples

Subsamples of less than 5 mm in length were extracted from each original yarn. Note that the fibres were manually extracted from the yarns, and the resulting length of around 5 mm does not represent their original length within the yarn. The fragments were placed on microscope slides and covered with cover slips. The samples were mounted at 90° to the initial laser polarization position (horizontally, following the long axis of the microscope slide). No further preparation was used to avoid contamination or damaged during handling and sample preparation.

2.4.2 Second harmonic generation (SHG) microscopy imaging

SHG imaging was performed at Synchrotron SOLEIL, thanks to a multiphoton Nikon A1 confocal MP + microscope (NIKON, France), combined with GaAsP NDD (gallium arsenide non-descanned) detectors and coupled with a tunable Mai Tai XF mode-locked Ti:sapphire femtosecond laser (SPECTRA PHYSICS, France). Experimental details are provided in Supplementary Information.

2.5 X-ray tomography measurements

Fibres and yarns were investigated by X-ray phase-contrast microtomography at the ANATOMIX beamline of Synchrotron SOLEIL [35], with a voxel size of 0.325 μm . Sample preparation and measurement protocols are detailed elsewhere [36]. The analysis, including segmentation, was performed with ImageJ and Avizo (Thermo Fisher Scientific) 2021.1 software.

2.6 Nano-mechanical investigations

A Multimode 8 Atomic Force Microscope (Bruker, Billerica, Massachusetts, USA) equipped with a RTESPA-525 probe (Bruker probes, Billerica, Massachusetts USA) was used to obtain indentation modulus mapping of the fibres cross-sections. Sample preparation and experimental details are provided in Supplementary information.

3 Results

Radiocarbon dating analysis of the Egyptian and Peruvian fishing net fibre samples suggests close estimated ages of the artefacts of 5350 ± 30 BP (between 4324 and 4053 calBCE) and 5265 ± 30 BP (between 4230 and 3986 calBCE, probability 95.4%), corresponding to the Neolithic period in Egypt and the Middle Pre-ceramic Period in southern Peru, respectively. The samples are well-preserved for scientific examination due to their desiccation in arid contexts.

In the ancient Egyptian yarn sample, the morphology of *cf. Linum usitatissimum* (flax) fibres is apparent from the presence of periodically occurring dislocations, (generally called ‘kink-bands’ in flax dedicated literature) along the length of the fibres. The term kink-bands is used here to refer to all microstructural irregularities visible under polarized light microscopy [27], attributed to local disorientation in the cellulose microfibril orientation. Kink-bands are sites of stress-concentration and weakness along the fibre length and therefore are more prone to substantial structural damage (Fig. 2.E). Their polygonal cross-section is also highlighted through tomography investigations (Fig. 3.B), and the ancient flax fibres also sometimes appear to be hollow, with a large luminal cavity (Fig. 2.G).

The yarn from La Yerba III, south coast Peru, is made of bundles of plant fibres (Fig. 2.I, J). Though it can be seen that the fibres in the image show slightly twisted single fibres (Fig. 2.K), with morphology similar to cotton’s bean-shaped cross-sectional shape, we suggest that the plant can be identified as *cf. Asclepias* (milkweed) [14]. The milkweed fibres appear to have thick cell walls (Fig. 2. K, L), justifying their structural function in the bast of the plant. They appear to have a narrow central cavity, although this is probably because the fibre (and therefore lumen) is flattened.

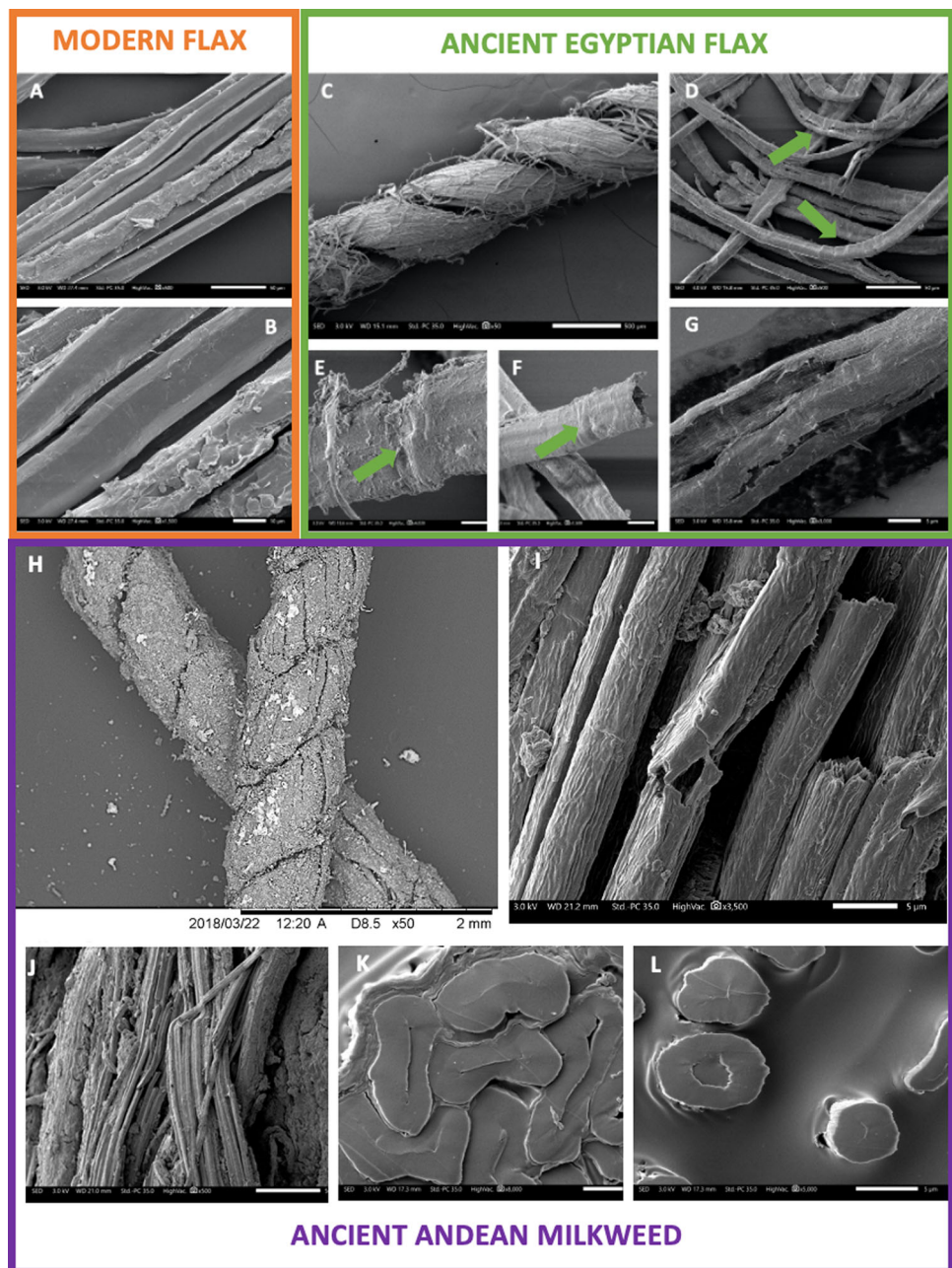
The SEM images indicate that the fibres do not exhibit the characteristic flatness and convolutions typically associated with cotton. While some individual fibres appear slightly flattened with faint convolutions (Fig. 2.K), this does not constitute definitive evidence of *G. barbadense*. This variety is often described as flattened with thickened edges, but such morphology, although indicative, is not sufficient to distinguish it reliably from other cotton types [37]. Instead, our identification relies on a broader set of observations rather than a single fibre.

Figure 2.I illustrates fibres from the fishing net, which appear in natural bundles consistent with vascular structures found in plant stems, a characteristic noted in milkweed fibres [38]. Bast fibres from the milkweed family exhibit elongated, tapering ends, occasional twists, and a slightly striated surface with fine longitudinal ridges. Notably, the flat and convoluted morphology typical of cotton is absent. However, some single fibres in Fig. 2.K display slight curling, which could be misinterpreted as cotton.

Notably, there are no visible dislocations or kink-bands on milkweed fibres, in contrast to those observed in long bast fibres such as hemp and flax [36]. The absence of a pronounced kink-band structure might be related to the fiber’s age or sampling even if kink-bands have already been observed in [34] on milkweed fibres found in the same archaeological site. However, the fibre organization in bundles and the presence of tissue remnants from the primary wall suggest that *cf. Asclepias* fibres originate from stems rather than floss, as previously proposed. Polarized Light Microscopy (PLM) further reveals fibre bundles and some hints of dislocations (Supplementary Fig. 2).

The architecture of the two yarns is similar. However, both samples are made by plying two single S threads into Z direction used in the Egyptian flax thread (Fig. 2.C) and similarly in the Peruvian milkweed thread (Fig. 2.H). As further discussed later both being spliced. The plying mode is one of the suggested indicators for identifying splicing in archeological textiles [39], a process used since the earliest textile manufacturing in the Levant region and Egypt [40]. Other indicators for splicing are thread diameter regularity, minimal twist, smooth appearance of the thread, as well as some degree of retting. On Peruvian milkweed fibre samples,

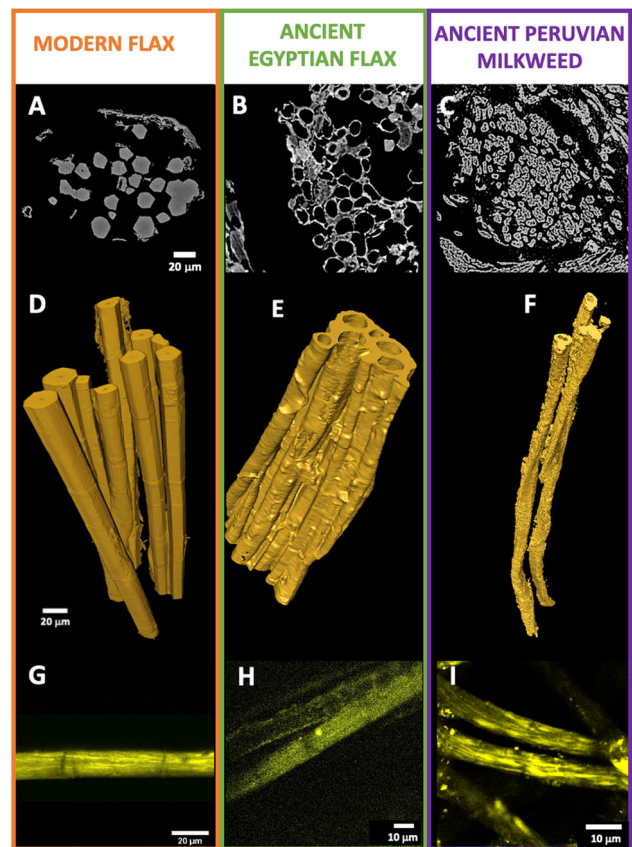
Fig. 2 SEM images of the reference modern flax (A,B), ancient Egyptian flax (C–G), and Ancient Peruvian milkweed (H–N). Damage is clearly evidenced on ancient flax with hollow fibres (D, F, G), and structural cracks are visible (E, G). The bean-like shape of milkweed fibres is clearly evidenced (L–N) and the fibres seem to be better preserved (J, K) with less visible damage and smooth surfaces. Kink-bands are indicated using green arrows on D, E, and F



some parameters are difficult to evaluate due to the external coating of the yarn, possibly used for protection, or applied to help the splicing process [41]; the presence of a coating is clearly observed after a gentle water treatment in the laboratory (Fig. 2.H). Regarding fibre retting, we notice good individualization of elementary flax fibres (Fig. 2.D) with fluffy regions where individual fibres are sticking out, possibly induced by the wear and tear of the products (Fig. 2.C); this is also observed in samples of modern flax (Fig. 2.A, B). This type of degradation was observed by Hearle et al. and associated with wear and repeated washing of garments, but can also result from preliminary treatments applied to the yarns, such as wet finishing and smoothing to give them suppleness [42]

Interestingly, tomography supplies volumetric information. Supplementary Fig. 3 shows cross-sections of both Egyptian and Peruvian thread. As highlighted by these observations, we cannot exclude the use of both milkweed fibres, from seeds and bast fibres from the stem. This mix of both fibres spliced into the 2SZ threads can explain why the cf. *Asclepias* sample is so irregular (Fig. 2.H). Nevertheless, the next investigations, i.e. multiphoton microscopy, tomography focus (Fig. 3) and AFM (Fig. 4), have been performed in the bast and not seed fibres region of the thread, as demonstrated by their lumen filling and also their cross-section size.

Fig. 3 Investigation of the structure of fibres through micro-CT (A–F) and SHG microscopy (G–I). Cross-sections and longitudinal 3D views of modern flax (A, D), ancient Egyptian flax (B, E), and ancient Peruvian milkweed (C, F). Multiphoton microscopy scans of modern flax (G), ancient Egyptian flax (H), and ancient Peruvian milkweed (I). A, B, C and D, E, F have the same scale. For cf. *Asclepias*, bast fibres have been selected

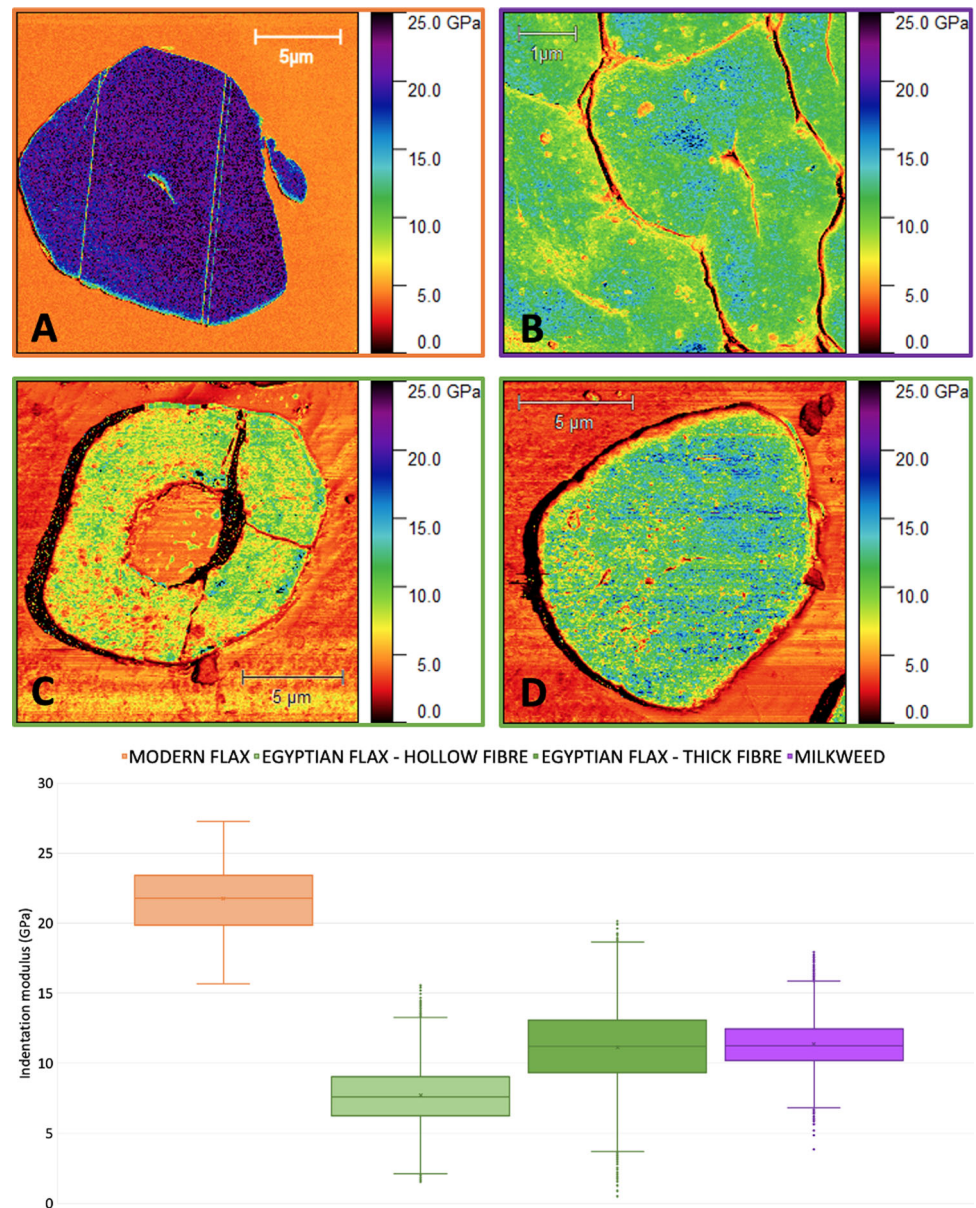


Fibre individualization is more difficult to assess for the Peruvian milkweed sample even if individualization seems good in Fig. 3.C and F. It should be noted that the middle lamellae, which adjoins elementary fibres into bundles, are very sensitive to ageing [43] and may have been degraded and removed over time. While the diameters for the flax and milkweed threads are in the same range (around 0.6 mm for Egyptian flax yarn and 0.8–0.9 mm for Peruvian milkweed yarn), the milkweed thread is more irregular, with significant variations between the two single threads of the yarn (Fig. 2.H). Finally, the twisting of the single threads remains relatively low, with angles between 5 and 25 degrees. These observations suggest that both yarns were made by end-to-end splicing rather than by continuous splicing [14]. Notably, in Egypt, transition from continuous splicing to end-to-end splicing occurred around 5500 BP [44], i.e. around the time our sample was created.

Time-related ageing has a strong effect on the chemical and mechanical properties of organic textile objects [45], especially due to the action of microorganisms and water [46], both penetrating the fibre cell walls through the lumen and kink-band regions [47]. To illustrate such defects and potential damage, Fig. 3 focuses on the inner structure and morphology of the flax and milkweed fibres. Micro-tomography (Fig. 3. A, B, C, D, E, F) and Second Harmonic Generation (SHG) microscopy (Fig. 3.G, H, I) were used, and comparison with modern flax fibres is included (Fig. 3.A, D, G).

In Fig. 3.B, the polygonal shape of ancient flax fibres is visible (especially on undamaged fibres); but compared to modern flax (Fig. 3.A), ancient Egyptian flax fibres (Fig. 3.B) are highly damaged and their lumen is often enlarged, which is also observed in our case through SEM (Fig. 2.F, G) [48] and tomography (Fig. 3.E). For more details on the microstructure of the Egyptian fishing net fibre, especially in kink-band zones, the reader can refer to [49] where a dedicated tomography investigation is proposed. This is likely due to the fact that degradation of the cell walls starts internally from the lumen cavity, due to the conjugated effect of humidity and enzymes or microorganisms. This peculiar biodegradation mechanism has also been observed on modern flax fibres degraded in a garden compost [50]. Only a minor fraction of old flax fibres remain cellulose-filled, with relatively light damage. 3D scans further highlight the hollow shape and irregular surface of old flax fibres compared to modern flax. The main features of milkweed fibres are their small diameter (approx. 8–12 µm) compared to flax (13–17 µm), their slightly twisted shape (Fig. 3.F) and their elongated cross-section, possibly due to a large, but flattened lumen. While these characteristics may *prima facie* suggest strong similarity with cotton trichomes, the internal morphology of milkweed fibres is substantially different with a large lumen, reaching up to 77% of the cross-sectional area [51]. Moreover, milkweed fibres exhibit a specific biochemical composition—cellulose (39%), hemicellulose (36%), and lignin (18%) [52]—more similar to wood fibres than flax fibres. The cellulose content is much higher in flax fibres, (65–80%) [53], and around 60% of this cellulose is crystalline [43] against 45–53% for milkweed fibres [54]. These differences in composition may affect ageing behaviour, especially as the lignin content is very low for flax (below 2% [53]). Goudenhoft et al.

Fig. 4 Mapping of cell wall indentation modulus obtained through AFM in PeakForce QNM mode on reference modern flax (A), ancient Peruvian milkweed (B), and ancient Egyptian flax (C, D). Moustache boxes show the data dispersion (E). For cf. *Asclepias*, bast fibres have been selected



have published a comparative biochemical assessment of modern and ancient flax fibres; the main conclusions demonstrate that the cellulose content is not greatly impacted by long-term ageing (82.7% of cellulose expressed as % of total monosaccharides for modern flax against 91.6% for the ancient flax), oppositely, non-cellulosic monosaccharides are much more reduced (for example, a decrease of -80% of the galactose content associated to rhamnogalacturonan type-I parietal polymers was addressed for ancient flax).

Some age-related degradation in milkweed fibre ultrastructure is also visible through SHG investigations. The SHG signal is mainly generated by crystalline cellulose, as a non-centrosymmetric molecule. Cellulose macrofibrils are clearly visible in modern flax (Fig. 3.G) and milkweed fibres (Fig. 3.I) with a pronounced preferred orientation ($5\text{--}10^\circ$) of these macrofibrils relative to the axis of the fibre, suggesting a mechanical function of the macrofibrils both for milkweed fibres and for flax fibres. The SHG signal from ancient flax (Fig. 3.H) is very low, in agreement with tomographic and SEM images, the material being damaged and its quantity and volume reduced by ageing.

The studied fibres were identified as cf. *Asclepias* primarily due to their bast-like structure, cohesive bundling, and high lumen filling, as seen in tomography and SEM datasets, and supported by the regional absence of cotton at the time. Other fibre candidates (cotton, soft-stem plants, seed hairs) were excluded using a multi-methodological approach combining multiphoton microscopy, tomography and SEM. The identification is cautious, using relative terminology (“cf.”), and follows current best practices by relying

on multiple distinguishing and characteristic features, not single diagnostics. This approach enhances future reproducibility and prepares for the possibility of encountering new, undocumented fibre species in archaeological contexts.

Plant fibre mechanical properties strongly correlate with the orientation of cellulose microfibrils, biochemical composition, and cellulose crystallinity. We investigated the local mechanical properties of the sample cell walls using atomic force microscopy in PeakForce QNM mode to obtain a high-resolution mapping of indentation modulus. On ancient fibres, characterization is generally done by spectroscopy and imaging such as optical or electronic microscopy. In this paper, we wanted to add local mechanical measurement because mechanical information are valuable for characterizing damages which are not necessarily observable by other techniques. For example, changes in biochemical composition can induce important modifications in mechanical performances [48]. Also, combined with known changes in biochemical composition, local mechanical measurements can help suggest regions (e.g. in the cross-section) where biochemical changes have had most impact. In the present case, mechanical properties are an indicator of preservation along time, giving precious information on the ability of the cell walls to have a long-term sustainable behaviour.

A very homogenous indentation modulus (21.4 ± 2.7 GPa) is measured for modern flax (Fig. 4.A), which is in agreement with previously published results [43, 55]. We can observe a regular hexagonal shape and a small lumen, representing only 1–2% of the fibre cross-section. The ancient milkweed fibres have a lower stiffness with an average indentation modulus of 10.9 ± 1.7 GPa, possibly due to the lower cellulose content but also due to the ageing process, which may strongly decrease the content of non-cellulosic polymers in the fibres and thus reduce the mechanical property of the cell wall matrix which has a significant effect on the indentation modulus. We also notice significant heterogeneity in the stiffness measurements, with small regions around 20 GPa and others less than 10 GPa, revealing non-uniform degradation. Two ancient flax fibres investigated, one with a large central cavity and another one with a low-size lumen, exhibit average indentation moduli of 7.2 ± 2.1 GPa and 10.8 ± 2.9 GPa, respectively, with non-uniform ageing behaviour and large variations in stiffness (between 5 and 20 GPa depending on the region). It is worth noting that there are fewer areas of high stiffness in the ancient flax sample with the large lumen (as opposed to the sample with the small lumen), as the large lumen is a result of—as well as promotes—more biochemical age-related degradation.

4 Discussion

Combining archaeometry, botany and materials science, we compare the use of two distinct indigenous bast fibres (flax and milkweed) in Egypt and Peru at the same pre-historic period (Predynastic Egypt and Preceramic Peru) for the fabrication of fishing nets. We specifically focus on thread and fibre processing and the evolution in fibre structure and properties over time to offer new insights on ageing behaviours of distinct fibre species.

The flax plant was already domesticated, and its fibres were being extensively harvested, prior to the Neolithic period in the Nile Valley cultivation area, while milkweed was part of the local vegetation in the river valleys of the south coast of Peru and it was being gathered as a wild resource during the Middle Preceramic. Issues of resource management and availability are paramount from a societal perspective [34, 56]. The Egyptian society had well-established agriculture and flax resources almost guaranteed by fertile soils irrigated by seasonal Nile floods. This enabled a pre-historic textile sector to be set up and local skills and crafts to be developed, but with moderate energy and manual labour. In the case of Peruvian Middle Preceramic marine hunter-gatherers, a significant part of textile craft work involved collecting wild plants and extracting fibre bundles, so that fibre production could not be controlled completely. Nonetheless, textile manipulation technologies were highly developed by selecting suitable plant fibres the splicing cf. *Asclepias* bast fibres perfectly suited to their targeted use, i.e. fishing net manufacturing, both in terms of morphology and performance, although they had more limited initial intrinsic characteristics (as discussed later): all highlighting the considerable fibre technology capabilities developed by the Preceramic marine hunter-gatherers of the Pacific coast of Peru. This included, not least, more preparatory work before for the thread making whose elementary fibres were less suitable for splicing because they were typically shorter than flax fibres [57]. Their threads were almost certainly prepared by thigh-splicing [14]. In both South American and Egyptian cases, aquatic resources were key, thanks to proximity to the Pacific Ocean or the Nile. These enabled for instance the processing of plants by water retting to separate and extract bast fibres more easily. This was likely finely controlled because if it was overdone too much fibre separation could compromise the later elaboration into yarn during splicing. If this occurred, it probably required reattaching fibres using saliva [58] or some other coating substance such as animal glues or water-based adhesives [41].

While we cannot be certain that either of these fishing net fragments were actually deployed in water in the distant past (although this would seem very likely), a feature of this study is their subsequent degradation over millennia. The two types of fibre have distinct structure and biochemistry. We find the cf. flax fibres to be in a poorer state of preservation than the cf. milkweed fibres, which is particularly visible in their structure, as seen in the SEM images, but also in their ultrastructure. Organic materials like plant fibres are rarely found in archaeological sites. Generally, dry and hot or dry and cold environments are ideal for their preservation. Biodegradation, especially when combined with high humidity, is a major factor in the loss of textile finds. In addition, certain environments, such as acidic, are known to accelerate the degradation of bast fibres [59]. However, certain processes, such as mineralization (where metal ions replace organic material), or an alkaline/acid pH and anoxic environment (which prevents the growth of fungi and bacteria), can help preserve the fibres' structure despite biochemical changes within the cells [60, 61].

A recent study showed that the lack of oxygen and light—factors that prevent oxidation and photodegradation—slowed the degradation of textiles found in Egyptian coffins used for funerary purposes [62]. Indeed, no microorganism can degrade lignin in an anoxic environment [61], and cellulose oxidation and hydrolysis are also reduced.

It is remarkable that another Egyptian fishing net from the Louvre museum studied in [27, 62] showed similar degradation patterns to the fishing net discussed in this paper, confirming the consistency of our observations. The exceptional preservation of these objects, which were made for fishing (a purpose that usually involves significant exposure to water), suggests that both Egyptian fishing nets likely underwent a similar degradation process despite the environmental challenges. The fact that these archaeological objects have survived to this day indicates they were probably buried quickly and deeply enough to limit exposure to oxygen and light. It is also possible that the ancient Egyptians applied treatments, such as waxes or oils, which would have made the nets waterproof and provided a barrier against microorganisms, which helped in their preservation.

The flax fibres have numerous kink-bands, which are not observed in the milkweed fibres, suggesting a soft extraction of the latter. Wear patterns on an *Argopecten purpuratus* shell, along with the presence of numerous lithic scrapers at La Yerba III, may indicate tools used for extracting bast fibres and performing decortication. This evidence suggests that the plants may not have undergone retting or were subjected to only a very subtle retting process. [34]. Kink-band regions are critical entry points for water and microorganisms into the cell wall and can facilitate biodegradation in the same way as the fibre lumen. The lumen can act as a conductive channel, as has been demonstrated during ageing of flax fibres in compost [50]. In our sample, few fibres are unaffected by the degradation process and remain fully intact. The signals obtained by multiphoton microscopy also testify to both the quantitative and qualitative reduction in crystalline cellulose. This is not the case for the cf. *Asclepias* fibres, which have a relatively well-preserved structure. In their native state, they already have very pronounced lumens [51], and despite this and the opportunity for water to penetrate to the heart of the fibres, they are better preserved than the flax fibres. This resistance to long-term ageing can be explained by their biochemical composition and in particular by their high lignin content [52]. Lignin's hydrophobic nature generally offers protection against water-related damage, as is the case in the sap-conducting cells of plants or in coconut fibres, for example. All of these observations and hypotheses are confirmed by the stiffness of the cell walls measured by AFM. While the GPa values provide useful information on the mechanical properties of individual fibres, we fully acknowledge that the overall durability of the yarn depends largely on its structural characteristics and that resistance to long-term ageing can also be influenced by environmental conditions and especially in case of aerobic environment, which highly limits the degradation sensitive components, such as pectins or labile hemicelluloses. Moreover, the heterogeneity in stiffness in flax fibres indicates pronounced local degradation, whereas this is not as evident in milkweed fibres. Overall damage to the cell walls is due to degradation of cellulose and some non-cellulose polymers which are sensitive to moisture-related ageing. In the case of milkweed fibres, the high lignin content reduces this degradation, and under certain ageing conditions, the lignin can even cross-link with the xylans [63], ensuring better cohesion and damage prevention.

5 Conclusion

It is striking to note how two ancient societies used distinct indigenous plant resources with very different properties to each successfully develop well-tuned *chaînes opératoires* and textile artefacts for the same function and use. This demonstrates peoples' ability to adapt and exploit local natural resources and environments towards subsistence: here exemplified by fishing. From the perspective of a multidisciplinary research approach, this study also demonstrates the importance of plant fibre structure and composition on long-term degradation and ageing. It gathers important findings about the long-term behaviour of plant fibres, which is crucial knowledge for developing new sustainable and performing bio-based composite materials.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request. The manuscript has associated data in a data repository.

Declarations

Conflict of interest The authors declare no conflict of interest.

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References

1. W. Van Zeist, J.A.H. Bakker-Heeres, Evidence for linseed cultivation before 6000 bc. *J. Archaeol. Sci.* **2**, 215–219 (1975). [https://doi.org/10.1016/0305-4403\(75\)90059-X](https://doi.org/10.1016/0305-4403(75)90059-X)
2. S. Harris, Smooth and cool, or warm and soft; investigating the properties of cloth in prehistory, in *North European symposium for archaeological textiles*. ed. by A. Strand, M. Gleba, U. Mannering, C. Munkholt, M. Ringgaard (Oxford Boo, Oxford, 2009), pp.104–112
3. S. Harris, 2014 Flax fibre: Innovation and Change in the Early Neolithic A Technological and Material Perspective, In: *Textile Society of America Symposium Proceedings*, Los Angeles, California, 10–14
4. T. Schick, 1988. Nahal Hemar Cave : Cordage, Basketry and Fabrics, Atiqot
5. M. Hopf, 2008 Plant remains and early farming in Jericho 1, In: G Dimbleby (Ed.), *The Domestication and Exploitation of Plants and Animals*, New York, USA
6. F.C. Wild, J.P. Wild, Sails from the Roman port at Berenike, Egypt. *The Int. J. Nautical Archaeol.* **30**, 211–220 (2001). <https://doi.org/10.1006/ijna.2001.0354>
7. J. Whitewright, Roman rigging material from the Red Sea port of Myos Hormos. *Int. J. Naut. Archaeol.* **36**, 282–292 (2007). <https://doi.org/10.1111/j.1095-9270.2007.00150.x>
8. L. Blue, 2002 Myos Hormos/Qušeir al-Qadīm. A Roman and Islamic port on the Red Sea coast of Egypt — A maritime perspective, *Proceedings of the Seminar for Arabian Studies* 32 139–150
9. E. Vanhaute, Between patterns and processes: measuring labor markets and family strategies in Flanders, 1750–1990. *Hist. Fam.* **2**, 527–545 (1997). [https://doi.org/10.1016/S1081-602X\(97\)90028-2](https://doi.org/10.1016/S1081-602X(97)90028-2)
10. B.L. Hardy, M.-H. Moncel, C. Kerfant, M. Lebon, L. Bellot-Gurlet, N. Mélard, Direct evidence of Neanderthal fibre technology and its cognitive and behavioral implications. *Sci. Rep.* **10**, 4889 (2020). <https://doi.org/10.1038/s41598-020-61839-w>
11. L. Meunier, M. Guyon, 2020 Waterproofing material from a 2nd Century AD barge from Lyon: Looking from the Roman how)know to caulk with pitched textiles, In: *Redefining Ancient Textile Handcraft Structures, Tools and Production Processes*, Granada, Spain
12. P. Pomey, P. Poveda, Gyptis: sailing replica of a 6th-century-BC archaic Greek sewn boat. *Int. J. Naut. Archaeol.* **47**, 45–56 (2018). <https://doi.org/10.1111/1095-9270.12294>
13. B. Dimova, S. Harris, M. Gleba, Naval power and textile technology: sail production in ancient Greece. *World Archaeol.* **53**, 762–778 (2021). <https://doi.org/10.1080/00438243.2021.2015428>
14. D. Beresford-Jones, A. Pullen, G. Chauca, L. Cadwallader, M. García, I. Salvatierra, O. Whaley, V. Vásquez, S. Arce, K. Lane, C. French, Refining the maritime foundations of Andean civilization: how plant fiber technology drove social complexity during the preceramic period. *J. Archaeol. Method Theory* **25**, 393–425 (2018). <https://doi.org/10.1007/s10816-017-9341-3>
15. M. Moseley, 1975 *The maritime foundations of Andean civilization*, Cummings A
16. FAO, 2020 *The State of World Fisheries and Aquaculture 2020. Sustainability in action*, Agriculture Organization of the United Nations
17. M.E. Endress, S. Liede-Schumann, U. Meve, An updated classification for Apocynaceae. *Phytotaxa* **159**, 175–194 (2014)
18. A.G. Whiting, 1943. A Summary of the Literature on Milkweeds (*Asclepias* Spp.) and Their Utilization, *Miscellaneous* 330497 <https://doi.org/10.22004/ag.econ.330497>
19. J. Rossen, T.D. Dillehay, D. Ugent, Ancient cultigens or modern intrusions?: evaluating plant remains in an Andean case study. *J. Archaeol. Sci.* **23**, 391–407 (1996). <https://doi.org/10.1006/jasc.1996.0035>
20. O.T. Westengen, Z. Huamán, M. Heun, Genetic diversity and geographic pattern in early South American cotton domestication. *Theor. Appl. Genet.* **110**, 392–402 (2005). <https://doi.org/10.1007/s00122-004-1850-2>
21. E. Kallenbach, Fiber artifacts from the Paisley Caves: 14,000 years of plant selection in the Northern Great Basin. *Am. Antiq.* **89**, 238–262 (2024)
22. E. Kallenbach, Testing the feasibility of fiber identification for fine cordage artifacts from the Paisley Caves, Oregon. *J. Archaeol. Sci.* **158**, 105855 (2023). <https://doi.org/10.1016/j.jas.2023.105855>
23. J.A. Suomela, K. Vajanto, R. Räisänen, Seeking nettle textiles – utilizing a combination of microscopic methods for fibre identification. *Stud. Conserv.* **63**, 412–422 (2018). <https://doi.org/10.1080/00393630.2017.1410956>
24. J.A. Suomela, K. Vajanto, R. Räisänen, Examining the white Karelian textile tradition of the late nineteenth century—focus on plant fibers. *Textile* **18**, 298–324 (2020). <https://doi.org/10.1080/14759756.2019.1699365>
25. A. Bourmaud, L. Pinsard, E. Guillou, E. De Luycker, M. Fazzini, J. Perrin, T. Weitkamp, P. Ouagne, Elucidating the formation of structural defects in flax fibres through synchrotron X-ray phase-contrast microtomography. *Ind. Crops Prod.* (2022). <https://doi.org/10.1016/j.indcrop.2022.115048>
26. L. Kozlova, A. Petrova, A. Chernyad'ev, V. Salnikov, T. Gorshkova, On the origin of bast fiber dislocations in flax. *Ind. Crops Prod.* **176**, 114382 (2022). <https://doi.org/10.1016/j.indcrop.2021.114382>
27. L. Morgillo, C. Goudenhooff, A. Melelli, S. Durand, M. Abida, J. Beaugrand, A. Bourmaud, Impact of flax fibre kink-bands on local longitudinal mechanical properties and cell wall ultrastructure. *Compos. Part A Appl. Sci. Manuf.* **191**, 108754 (2025). <https://doi.org/10.1016/j.compositesa.2025.108754>
28. D. Quereilhac, L. Pinsard, E. Guillou, M. Fazzini, E. De Luycker, A. Bourmaud, M. Abida, J. Perrin, T. Weitkamp, P. Ouagne, Exploiting synchrotron x-ray tomography for a novel insight into flax-fibre defects ultrastructure. *Ind. Crops Prod.* **198**, 116655 (2023). <https://doi.org/10.1016/j.indcrop.2023.116655>

29. H. Lukesova, B. Holst, Identifying plant fibres in cultural heritage with optical and electron microscopy: how to present results and avoid pitfalls. *Herit. Sci.* **12**, 12 (2024). <https://doi.org/10.1186/s40494-023-01122-z>
30. M. Krifa, S. Stewart Stevens, Cotton utilization in conventional and non-conventional textiles—a statistical review. *Agric. Sci.* **7**, 747–758 (2016)
31. R.A. Benfer, AMERICAS, SOUTH Early Villages, in *Encyclopedia of Archaeology*, ed. by D.M. Pearsall (Academic Press, New York, 2008), pp.368–380
32. F.-A. Engel, 1991. Un desierto en tiempos prehispánicos: río Pisco, Paracas, río Ica, CIZA
33. J. Quilter, E.B. Ojeda, *Society and mortuary practices in a preceramic peruvian village* (University of Iowa Press, Iowa city, 1989)
34. C. Alday, M.A. García, C. Alarcón, D. Beresford-Jones, The use and context of fiber plants during the middle preceramic: evidence from La Yerba II and III, south coast of Peru. *Frontiers Environ. Archaeol.* **2**, 1251137 (2023). <https://doi.org/10.3389/fearc.2023.1251137>
35. T. Weitekamp, M. Scheel, J. Perrin, G. Daniel, A. King, V. Le Roux, J.L. Giorgetta, A. Carcy, F. Langlois, K. Desjardins, C. Meneglier, M. Cerato, C. Engblom, G. Cauchon, T. Moreno, C. Rivard, Y. Gohon, F. Polack, Microtomography on the ANATOMIX beamline at Synchrotron SOLEIL. *J. Phys. Conf. Ser.* **2380**, 012122 (2022). <https://doi.org/10.1088/1742-6596/2380/1/012122>
36. A. Bourmaud, L. Pinsard, E. Guillou, E. De Luycker, M. Fazzini, J. Perrin, T. Weitekamp, P. Ouagne, Elucidating the formation of structural defects in flax fibres through synchrotron X-ray phase-contrast microtomography. *Ind. Crops Prod.* **184**, 115048 (2022). <https://doi.org/10.1016/j.indcrop.2022.115048>
37. J.A. Suomela, M. Viljanen, K. Svedström, K. Wright, S. Lipkin, Research methods for heritage cotton fibres: case studies from archaeological and historical finds in a Finnish context. *Herit. Sci.* **11**, 175 (2023). <https://doi.org/10.1186/s40494-023-01022-2>
38. N. Reddy, Y. Yang, Properties of natural cellulose fibers from hop stems. *Carbohydr. Polym.* **77**, 898–902 (2009). <https://doi.org/10.1016/j.carbpol.2009.03.013>
39. M. Gleba, S. Harris, The first plant bast fibre technology: identifying splicing in archaeological textiles. *Archaeol. Anthropol. Sci.* **11**, 2329–2346 (2019). <https://doi.org/10.1007/s12520-018-0677-8>
40. M. Gleba, 2020 Unraveling the Fabric of the Past, In: Companion to Textile Culture, Wiley Hoboken. 11–25
41. W.D. Cooke, M.M. El-Gamal, A. Brennan, 1991 The hand spinning of ultra-fine yarns, Part 2: the spinning of flax
42. J.W.S. Hearle, B. Lomas, W.D. Cooke, 42—Mechanical Wear In Ancient Textiles, in *Atlas of Fibre Fracture and Damage to Textiles*, 2nd edn., ed. by J.W.S. Hearle, B. Lomas, W.D. Cooke (Woodhead Publishing, Sawston, 1998), pp.382–389. <https://doi.org/10.1533/9781845691271.8.382>
43. A. Melelli, D.U. Shah, G. Hapsari, R. Cortopassi, S. Durand, O. Arnould, V. Placet, D. Benazeth, J. Beaugrand, F. Jamme, A. Bourmaud, Lessons on textile history and fibre durability from a 4000-year-old Egyptian flax yarn. *Nat. Plants* **7**, 1200–1206 (2021)
44. H. Granger-Taylor, *Evidence for linen yarn preparation in Ancient Egypt—the hanks and fibre strips and the balls of prepared rove from Lahun in the Petrie Museum of Egyptian Archaeology, University College London (UC 7421, 7509 and 7510)* (Lahun Studies. SIA Publishing, Reigate, 1998), pp.102–111
45. I. Good, Archaeological textiles: a review of current research. *Annu. Rev. Anthropol.* **30**, 209–226 (2001). <https://doi.org/10.1146/annurev.anthro.30.1.209>
46. R.A. Blanchette, A review of microbial deterioration found in archaeological wood from different environments. *Int. Biodeterior. Biodegradation* **46**, 189–204 (2000). [https://doi.org/10.1016/S0964-8305\(00\)00077-9](https://doi.org/10.1016/S0964-8305(00)00077-9)
47. A. Hernandez-Estrada, H.-J. Gusovius, J. Müssig, M. Hughes, Assessing the susceptibility of hemp fibre to the formation of dislocations during processing. *Ind. Crops Prod.* **85**, 382–388 (2016). <https://doi.org/10.1016/j.indcrop.2016.01.006>
48. C. Goudenhoof, A. Melelli, S. Durand, X. Falourd, L. Le-Bot, L. Morgillo, S. Gaballah, R. Cortopassi, A. Quiles, D.U. Shah, F. Jamme, J. Beaugrand, A. Bourmaud, Comparison of kink-band structures and specificities of cell wall polysaccharides in modern and ancient flax fibres. *Carbohydr. Polym.* **344**, 122526 (2024). <https://doi.org/10.1016/j.carbpol.2024.122526>
49. L. Morgillo, A. Melelli, M. Scheel, R. Wightman, T. Weitekamp, C. Goudenhoof, A. Quiles, D.U. Shah, M. Abida, J. Beaugrand, A. Bourmaud, Inside the kink-bands of archaeological flax artefacts via sub-micrometer resolution micro-CT: a comprehensive microstructural analysis to better understand degradation mechanisms of fibres. *Compos. B Eng.* **298**, 112347 (2025). <https://doi.org/10.1016/j.compositesb.2025.112347>
50. A. Melelli, D. Pantoloni, E. Balnois, O. Arnould, F. Jamme, C. Baley, J. Beaugrand, D.U. Shah, A. Bourmaud, Investigations by AFM of ageing mechanisms in PLA-Flax Fibre composites during garden composting. *Polymers (Basel)* **13**, 2225 (2021). <https://doi.org/10.3390/polym13142225>
51. J.-Y.F. Dréan, J.J. Patry, G.F. Lombard, M. Weltrowski, Mechanical characterization and behavior in spinning processing of milkweed fibers. *Text. Res. J.* **63**, 443–450 (1993). <https://doi.org/10.1177/00405175930306300803>
52. C. Richard, P. Cousin, M. Foruzanmehr, S. Elkoun, M. Robert, Characterization of components of milkweed floss fiber. *Sep. Sci. Technol.* **54**, 3091–3099 (2019). <https://doi.org/10.1080/01496395.2018.1556691>
53. A. Bourmaud, J. Beaugrand, D.U. Shah, V. Placet, C. Baley, Towards the design of high-performance plant fibre composites. *Prog. Mater. Sci.* **97**, 347–408 (2018)
54. A. Sabziparvar, L. Boulos, M.R. Foruzanmehr, Effect of fiber length and treatments on the hygroscopic properties of milkweed fibers for superabsorbent applications. *Environ. Technol. Innov.* **28**, 102930 (2022). <https://doi.org/10.1016/j.eti.2022.102930>
55. O. Arnould, D. Siniscalco, A. Bourmaud, A. Le Duigou, C. Baley, Better insight into the nano-mechanical properties of flax fibre cell walls. *Ind. Crops Prod.* **97**, 224–228 (2017). <https://doi.org/10.1016/j.indcrop.2016.12.020>
56. C. Alday, 2022 The case of the La Yerba II and III sites, In: A. Dickey, M. Gleba, S. Hitchens, G. Longhitano (Eds.), *Exploring Ancient Textiles*, Oxbow Books, Oxford, <https://doi.org/10.2307/j.ctv2v6pcmg.12>
57. N. Tarabi, H. Mousazadeh, A. Jafari, J. Taghizadeh-Tameh, Evaluation of properties of bast fiber extracted from *Calotropis* (Milkweed) by a new decorticator machine and manual methods. *Ind. Crops Prod.* **83**, 545–550 (2016). <https://doi.org/10.1016/j.indcrop.2015.12.071>
58. R. Janssen, Barry J. Kemp and Gillian Vogelsang-Eastwood, The Ancient textile industry at amarna. *J Near East Stud* **65**, 156–157 (2006). <https://doi.org/10.1086/505011>
59. L.G. Thygesen, Quantification of dislocations in hemp fibers using acid hydrolysis and fiber segment length distributions. *J. Mater. Sci.* **43**, 1311–1317 (2008). <https://doi.org/10.1007/s10853-007-2284-4>
60. C. Reynaud, M. Thoury, A. Dazzi, G. Latour, M. Scheel, J. Li, A. Thomas, C. Moulh at, A. Didier, L. Bertrand, In-place molecular preservation of cellulose in 5000-year-old archaeological textiles. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 19670–19676 (2020). <https://doi.org/10.1073/pnas.2004139117>
61. F. Cappitelli, P. Principi, R. Pedrazzani, L. Toniolo, C. Sorlini, Bacterial and fungal deterioration of the Milan Cathedral marble treated with protective synthetic resins. *Sci. Total. Environ.* **385**, 172–181 (2007). <https://doi.org/10.1016/j.scitotenv.2007.06.022>
62. A. Melelli, C. Goudenhoof, S. Durand, A. Quiles, R. Cortopassi, L. Morgillo, A. Magueresse, J. Beaugrand, F. Jamme, A. Bourmaud, Revealing degradation mechanisms of archaeological flax textiles through the evolution of fibres’ parietal polymers by synchrotron deep-UV fluorescence. *Polym. Degrad. Stab.* **226**, 110826 (2024). <https://doi.org/10.1016/j.polymdegradstab.2024.110826>
63. Y. Yin, L. Berglund, L. Salm n, Effect of steam treatment on the properties of wood cell walls. *Biomacromol* **12**, 194–202 (2011). <https://doi.org/10.1021/bm101144m>