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IS CROSS-SECTION SHAPE A DISTINCT FEATURE IN PLANT FIBRE IDENTIFICATION?*

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Correct identification of textile fibres is an important issue in archaeology because the use of different materials can yield crucial information about the society that produced the textiles. Textiles made of plant and animal fibres can normally be easily distinguished, but to distinguish between different types of plant fibres, in particular different types of bast fibres, is difficult. Some years back it was shown that the features fibre diameter, lumen diameter, dislocation (nodes), and cross markings cannot be used on their own to distinguish between the typical bast fibres used for textiles in ancient Europe: flax, hemp, and nettle. Particularly not when only a few fibres are available for an examination so that statistical analysis is not possible, as is often the case in archaeology. The last two characterization features typically used to distinguish between bast fibres are cross-section shape and lumen shape. In this paper, we present a study of retted and unretted fibres (in the stem) of flax, nettle, and hemp, and show that also cross-section shape and lumen shape cannot be used as distinguishing features on their own.

KEYWORDS: PLANT FIBRE IDENTIFICATION, TEXTILES, ARCHAEOLOGY, FLAX, HEMP, NETTLE, CROSS-SECTION

INTRODUCTION

Archaeological evidence suggests that the first textiles were made of tree-bast and wild plant fibres, see for example (Barber 1991; Jørgensen 1992; Good 2001; Hurcombe 2010; Gleba and Mannering 2012), however, the actual use and choice of different textile plants throughout history based on archaeological textile finds has so far not been analysed systematically. The main problem has been that bast fibres (i.e. flax, nettle, and hemp), which were the most common textile fibres available in ancient Europe, look very similar. Unfortunately, there has been a tendency in the literature to identify plant fibres as flax on the sole basis of examinations with standard, white light, compound microscopy (Kvavadze *et al*. 2009; Bergfjord *et al*. 2010; Haugan and Holst 2014). A standard, white light microscopy examination looking at the long axis of fibre is sufficient to distinguish animal fibres and plant fibres (animal fibres have scales). However, as was shown, this is not enough to identify the plant fibre type (Bergfjord and Holst 2010; Bergfjord *et al*. 2012; Haugan and Holst 2014). We note that the same limitation applies to scanning electron microscopy. Thanks to its superior resolution and high depth of field, scanning electron microscopy can produce beautiful microscopy images of archaeological fibres, as demonstrated in a recent publication *Fibres: Microscopy of Archaeological Textiles and Furs* (Rast-

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Eicher 2016), but despite what is sometimes claimed, scanning electron microscopy cannot be used, on its own to identify specific bast fibre species. Wrong identifications will lead to a distorted picture of the relative importance of the various textile plants.

Fortunately, there exist other methods that can be applied in secure plant fibre determination: micro X-ray diffraction (Müller *et al*. 2006), identification of crystals in the associated tissue material of the fibres (Catling and Grayson 1982; Bergfjord and Holst 2010; Bergfjord *et al*. 2012), and the modified Herzog test (Herzog 1922, 1943, 1955; Petraco and Kubik 2004; Haugan and Holst 2013), as well as microchemical tests (Luniak 1953; Wülfert 1999). A recent paper demonstrated that reliable identification of the unusual textile fibre hop can be achieved with a combination of several of the techniques listed above (Lukešová *et al*. 2019). An earlier publication shows how nettle can, in some cases, be distinguished from hemp and flax using polarisation microscopy (Bergfjord and Holst 2010). Ongoing work is applying the use of polarisation microscopy in an attempt to identify plant fibre species outside Europe (Paterson *et al*. 2017; Smith *et al*. 2020). The application of combined tests on historical material can be challenging due to the degradation of fibres (Lukešová *et al*. 2017; Lukešová 2018). Unfortunately DNA analysis, which at first seems an obvious choice, has so far not proven to be a good method for archaeological plant fibres. Fibres contain very little DNA material and the retting process, which releases the bast fibres from the stem, promotes DNA degradation so that even modern fibres are difficult to identify with DNA analysis (Hofreiter *et al*. 2001; Dunbar and Murphy 2009).

Finally, it should be emphasized that when it comes down to proving the use of specific plants, that is, flax or hemp for textile production, the only, true evidence is well preserved textile finds, where a proper fibre identification can be performed. Textile imprints on ceramics and mineralized textile remains cannot be assigned to specific species, because such material estimations are simply unreliable.

The recent research on genetic diversity of flax (*Linum usitatissimum*) confirms its domestication around 10.000 years ago. There are strong indications that at first flax was mainly cultivated for the oil (Allaby *et al*. 2005, 63). Measuring the seed size of flax suggests the presence of different forms of flax for oil and for fibre production since at least the third millennium B.C. (Herbig and Maier 2011; Karg 2011). Early flax processing technology has been studied by several authors (Herbig and Maier 2011; Leuzinger and Rast-Eicher 2011; Maier and Schlichtherle 2011).

In Europe, one of the earliest and largest textile finds is from Late Neolithic lake settlements (4,200–2,800 cal. BC). It includes textiles made of flax (Rast-Eicher 1997; Körber-Grohne and Feldtkeller 1998; Rast-Eicher and Thijsse 2001). Hemp (*Cannabis sativa*) was known and used in the Neolithic period in the northern latitudes, from Europe to East Asia, but textile use of this plant has not been confirmed in the western Europe until the Iron Age (Barber 1991, 17–19). Fibres of the stinging nettle (*Urtica dioica*) are assumed to have been used since the Mesolithic (Hurcombe 2014, 55–57, 63). A direct proof was recently given through fibre identification of the 2,800-year-old Lusehøj Bronze Age Textile from Voldtofte, Denmark (Bergfjord *et al*. 2012).

AIMS AND OBJECTIVES

It has been suggested that standard, white light, compound microscopy may be sufficient to ensure identification if, instead of looking at the long axis of the fibre, fibre cross-sections are examined (Stratmann 1973, p. 108; Catling and Grayson 1982, p. 4). The characteristic features in the cross-section view are cross-section shape and lumen shape.

Table 1 presents an overview of what is considered the typical cross-section features for flax, hemp, and nettle as given in the literature:

Not all literature acknowledges cross-section features as suitable for identification. One author state that fibre cross-section shape of flax and hemp should not be used as a distinguishing feature (Herzog 1955, p. 319), and neither Petraco and Kubik (2004) nor Goodway (1987) refer to typical cross-section shapes of the plant fibres they have studied. Goodway even states that cross-sections of cells from different vegetable fibers tend to look very similar (Goodway 1987, p. 31). The same was the finding of Bergfjord and Holst who stated in their paper on how to distinguish nettle from flax and hemp that large cross-section variations can occur within individual species (Bergfjord and Holst 2010, p. 1192).

In this study we show that it is possible to find all different shapes of fiber cross-section listed above (polygonal, oval, rounded, flattened) in all studied species. It is quite possible that a specific cross-section shape is on average typical for a particular fibre, but growth conditions may alter shapes, and working with cultural heritage objects allows only very limited sample amounts. The risk of poor/wrong statistics is therefore high.

Fibres grow in a compact sclerenchyma layer in plant stems. Retting causes fiber release and swelling. Before starting this study, we speculated that the extraction of fibres from the compact layer through retting may lead to the polygonal shapes becoming rounder. We noticed that some authors comment on fibres in stems (Bodros and Baley, 2008, p. 2144; Catling and Grayson 1982, pp. 12–23; Herzog 1955, p. 319, 335, 345), while others comment on extracted fibres (Carr *et al*, 2008, p. 81; Luniak 1953, p. 109, 124–125; Suomela *et al*. 2017, p. 419; Wülfert 1999, pp. 274–278), which is a potential source of confusion. Therefore, we decided to compare cross-section shapes and lumina of both processed (retted) and unprocessed fibres (in the stem).

Another danger we want to highlight may happen during actual sample preparation. Comparing cross-section shape is only possible when the cross-section is examined perpendicular to the fibre's longitudinal axis. However, historical fibres are often deformed in both spin and weave directions. It may be very difficult to prepare perpendicular cross-sections of degraded fibres because they keep their shape of spin due to loss of flexibility. They also tend to break easily.

Flax is usually harvested for fibre production when the bases of the plants begin to turn from green to yellow (Tobler 1938, p. 31) and seeds begin to ripen (Cook, 1959, p. 7). However, it is described that the exact time of harvesting was dictated by the ultimate use of fibres—green stems were harvested for soft fibres for very fine textiles. For a stronger cloth, the stems were left until they became yellow (Gale and Cutler, 2000, p. 152). Based on these references, we decided to investigate both mature and immature flax (*Linum usitatissimum*) as well as mature hemp (*Cannabis sativa*) and mature stinging nettle (*Urtica dioica*).

EXPERIMENTAL

The first batch of flax plants (*Linum usitatissimum*) was harvested in the botanical garden of the University Museum of Bergen in their immature state when the plants were completely green and started to blossom. A second batch was harvested six weeks later in its mature state when the stems started to be yellow in the lower part and the seeds began to ripen. Hemp (*Cannabis sativa*) was obtained from the botanical garden of the Natural History Museum in Oslo. We investigated a stem from a female individual in its mature state. Wild stinging nettle (*Urtica dioica*) was harvested in Bergen in a mature state.

Table 1 *Overview of the typical cross-section features for flax, hemp and nettle as given in the literature*

Authors	*Flax Fibre cross-section shape*	*Flax Lumen cross-section shape*	*Hemp Fibre cross-section shape*	*Hemp Lumen cross-section shape*	*Nettle Fibre cross-section shape*	*Nettle Lumen cross-section shape*
Bergfjord and Holst 2010: 1192	Rounded Polygonal	Narrow, round Oval	Rounded Polygonal	Narrow, round Oval	Elongated Band formed	Larger
Bodros and Baley 2008: 2144 (fibres in stems)	-	-	-	-	Polygonal	Channel-like
Carr *et al*. 2008: 81 (ultimate fibres)	Polygonal (3–5 sides), thick cell wall	Small lumen	Polygonal (4–6 sides), cell wall thickness similar to flax	Larger lumen than flax	-	-
Catling and Grayson 1982: 12–23 (fibres in stems)	Pentagonal or hexagonal Rounded in outline	Both narrow and wide (50:50)	Angular with 4, 5 or 6 sides Oval Round	Small Round Elongated Irregular	-	-
Herzog 1955: 319, 335, 345 (fibres in stems)	Flattened Irregular oval Star-shaped Polygonal Rounded Irregular	Line-shaped Wide Elliptic	Flattened oval Polygonal	-	Flattened oval Kidney-shaped Round Band-like	-
Isenberg 1967: 166	Polygonal	Slit-like	Rounded edges	Broad, becomes like a line towards the end of fibre	-	-
Luniak 1953: 109, 124–125 (fibre bundles)	Mainly sharply polygonal Oblong with rounded corners	Mainly narrow round Oval Larger forms	Similar to flax	Similar to flax, often as a mere line and indistinct	-	-
Suomela *et al*. 2017: 419 (fibre bundles)	Polygonal	Round and small	-	-	Oval	Flat and long
Wülfert 1999: 274–278 (fibre bundles)	Regularly polygonal	Mature – thin Immature – thick	Rounded	Not that thin as flax	Irregular oval Flattened	Rather wide with remains of protoplasm

Preparation of cross sections

The first series of cross-sections were prepared from the middle part of the plant stems of flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), and nettle (*Urtica dioica*). Sections of stems were mounted in epoxy resin EpoFix ($n_D = 1.571$), cut with a diamond saw (Buehler IsoMet low-speed precision cutting machine), ground, and polished. Nikon compound microscope Eclipse Ci-POL equipped with CFI TU Plan Fluor EPI P objectives series was used for measurements.

The second series of cross-sections were prepared from retted and combed reference material of flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), and nettle (*Urtica dioica*). The raw material was neither bleached nor spun. Flax and hemp were obtained from the company HempFlax AB from the Netherlands, nettle was obtained from the company NFC GmbH from Germany. We are aware of numerous convarieties/varieties of the described species. However, the identification of textile fibres by means of microscopy does not go below the level of species and the common praxis is to define the reference samples as it is done here.

Cross-section plates, silk embedding fibres, and a razor blade were used for preparing samples. Glycerin ($n_D = 1.474$) was used at the top of the sample as a mounting medium. Leica compound microscope Ortholux II POL-BK equipped with NPL FLuotar P objectives series was used for measurements.

RESULTS

Here we present fibre cross-section shapes and lumen cross-section shapes that we identified in following species flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), and stinging nettle (*Urtica dioica* with unprocessed fibres (fibres in the stem) and processed (retted) fibres. For flax, unprocessed stem fibres are presented for both mature and immature plants.

The results of our measurements are summarized in tables 2 and 3. As can be seen, it is possible to find all identified shapes of cross-sections from table 1 in all studied fibres both in unprocessed and processed fibres. These are polygonal, polygonal slightly rounded, oval, irregular oval, uneven with rounded edges, and flattened. Lumina found in all studied species can be narrow round, oval, or irregular oval. They can also be wide of larger forms, slit-like, indistinct, and flattened.

Table 2 *Cross-section shapes of immature and mature flax, hemp, and nettle fibres*

	Shape of fibre cross-section	*Flax immature/ stem*	*Flax mature/ stem*	*Flax mature/ retted*	*Hemp/ stem*	*Hemp/ retted*	*Nettle/ stem*	*Nettle/ retted*
1	Polygonal	x	x	x	x	x	x	x
2	Polygonal slightly rounded	x	x	x	x	x	x	x
3	Oval	x	x	x	x	x	x	x
4	Irregular oval	x	x	x	x	x	x	x
5	Uneven, rounded edges	x	x	x	x	x	x	x
6	Flattened	x	x	x	x	x	x	x

Table 3 *Lumen shapes of immature and mature flax, hemp, and nettle fibres. The number and letters refer to the microscopy images below where the features are displayed*

	Shape of lumen cross-section	*Flax immature/ stem*	*Flax mature/ stem*	*Flax mature/ retted*	*Hemp/ stem*	*Hemp/ retted*	*Nettle/ stem*	*Nettle/ retted*
A	Narrow round	x	x	x	x	x	x	x
B	Oval	x	x	x	x	x	x	x
C	Irregular oval	x	x	x	x	x	x	x
D	Larger forms, wide	x	x	x	x	x	x	x
E	Slit like	x	x	x	x	x	x	x
F	Indistinct	x	x	x	x	x	x	x
G	Flattened/elongated	x	x	x	x	x	x	x

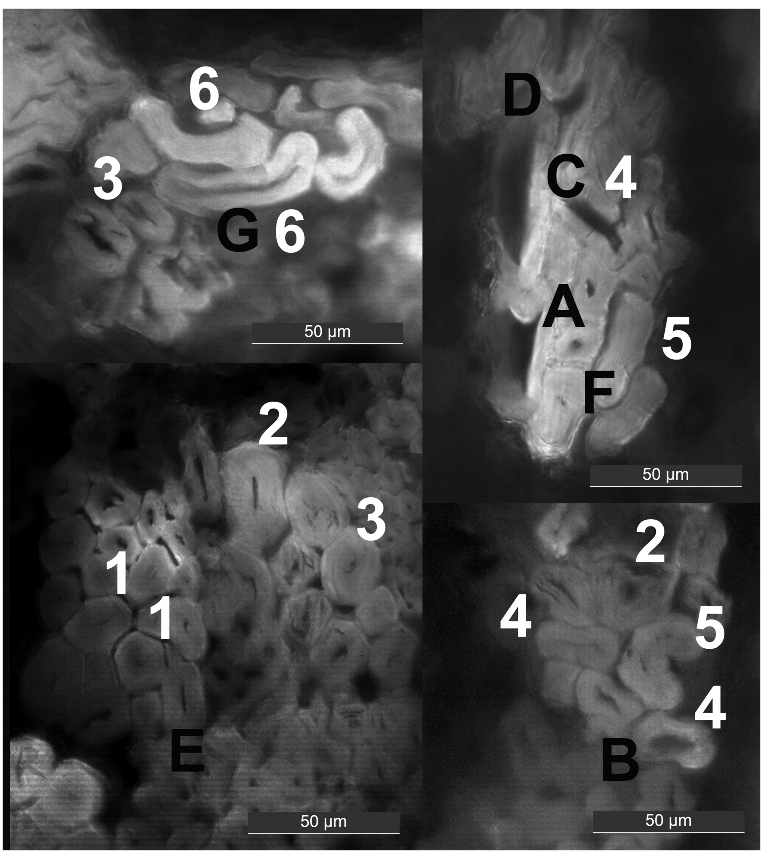

FIGURE 1 *Transmitted light micrograph of retted flax fibres. Numbers refer to the defined cross-section shapes from table 2. Polygonal, oval, flattened as well as all other forms are present. Letters refer to the defined shapes of lumina from table 3. Lumina are mostly narrow round, slit-like, and flattened, but all other forms are also present.*

Retted flax fibres show polygonal, rounded polygonal, oval, flattened, as well as all other forms (Fig. 1: cross-section shapes: 1, 2, 3 and 6). Their lumina are mostly narrow round, slit-like, and flattened, but all other forms are also present (Fig. 1: lumina A, E, G). Retted hemp fibres show polygonal, polygonal rounded, oval, flattened, as well as all other forms (Fig. 2: cross-section shapes: 1, 2, 3 and 6). Their lumina are narrow round but also of wider forms. Slit-like and flattened forms are present, as well as all other forms (Fig. 2: lumina A, D, E, and G). Retted nettle fibres mainly show oval and flattened forms; however, all other shapes are present as well (Fig. 3: cross-section shape 3 and 6). Lumina are often slit-like and flattened, but other forms are also present (Fig. 3: lumina E and G).

Fibres in mature flax and hemp stem typically show rounded polygonal outer shape with a narrow, round, or oval lumen. Fibres in immature flax and nettle stem mostly have a more flattened outer shape with a larger lumen. However, polygonal shapes can show up in nettle and flattened shapes are not unusual in mature flax and hemp. Figures of fibres in stem cross-sections are in supplementary document.

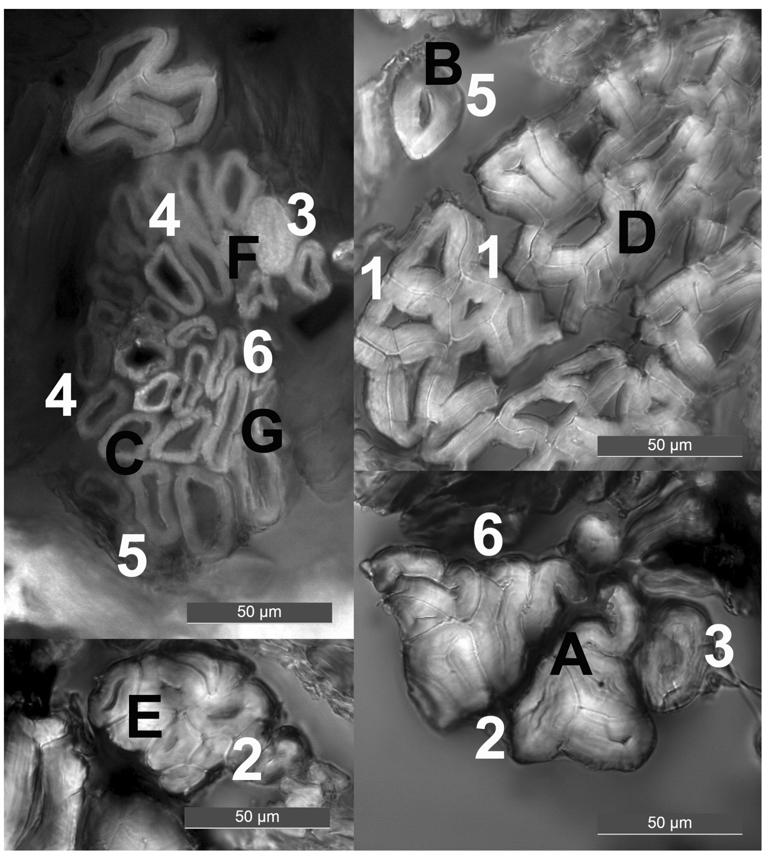

FIGURE 2 *Transmitted light micrograph of retted hemp fibres. Numbers refer to the defined cross-section shapes from table 2. Polygonal, oval, flattened as well as all other forms are present. Letters refer to the defined shapes of lumina from table 3. Lumina are often of wider forms, slit-like, and flattened are present, as well as all other forms.*

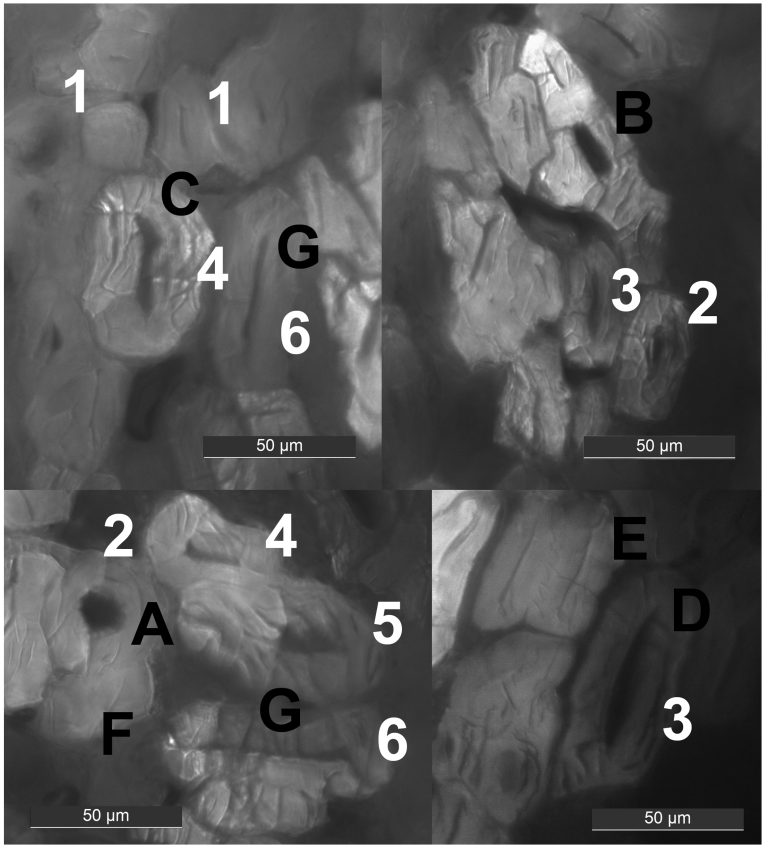

FIGURE 3 *Transmitted light micrograph of retted nettle fibres. Numbers refer to the defined cross-section shapes from table 2. Oval and flattened forms are common; however, all other forms are present as well. Letters refer to the defined shapes of lumina from table 3. Lumina are often slit-like and flattened, but other forms are also present.*

Our study shows that even cross-section shapes of unprocessed stems (that cannot be disturbed by processing or deformed due to spinning and/or weaving) cannot be used as a reliable feature for distinguishing species.

DISCUSSION

We have conducted a comparative study of fibre cross-section shapes and lumen cross-section shapes of three plant species (flax, hemp and nettle), and we summarize that the two criteria are inconclusive for identification on their own because fibres with non-characteristic shapes can be found for all species. We note that looking at the different images one does tend to recognize an overweight of fibres with what may be considered characteristic features, such as the rounded polygonal shape with a small lumen for mature flax and hemp, and flattened shape with a slit-like and flattened lumen for unmatured flax and nettle. However, the point we want to emphasize is that with only a very limited sample material that does not allow for a proper statistical analysis, it is very difficult to conclude. Also, for archaeological samples, nothing can be known about the growth conditions, and as we see, the very small lumen is characteristic for mature flax only.

CONCLUSION

In this study, we show that all identified shapes of fibre cross-sections and their lumina in flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), and stinging nettle (*Urtica dioica*), can be found in all three species. Flax was examined in two stages of ripeness: immature and mature because both were used for textile production. All identified shapes were found both in unprocessed and processed fibres. Mature flax and hemp typically show rounded polygonal outer shape with a narrow, round, or oval lumen. Immature flax and nettle mostly have a more flattened outer shape with a larger lumen. However, polygonal shapes can show up in nettle and flattened shapes are not unusual in flax and hemp.

We conclude that cross-section shape and lumen shape cannot be used on their own as a distinct feature for plant fibre identification. Proper identification is only possible by the combination of several methods, as highlighted in the introduction, and even then, secure identification cannot always be ensured. Precise knowledge of material use in cultural heritage collections is important for understanding resource management in the past. Hence, it is important to keep searching for new ways to identify plant fibre species in historical objects.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1: Cross-section shapes of immature and mature flax, hemp, and nettle fibres.
Table S2: Lumen shapes of immature and mature flax, hemp, and nettle fibres.
Figure S1: Reflected light micrograph of immature flax stem: the numbers refer to table 1. Oval and flattened shapes remind very much nettle fibres, polygonal- and polygonal, slightly rounded shapes are present as well as other types of shapes.
Figure S2: Reflected light micrograph of immature flax stem. The letters refer to table 2. Lumina are slit-like, flattened of wider forms, but all other forms are also present.
Figure S3: Reflected light micrograph of mature flax stem. The numbers refer to table 1. Polygonal- and polygonal slightly rounded cross section shapes can be observed, but oval and uneven shapes as well as all other forms are present.
Figure S4: Reflected light micrograph of mature flax stem: The letters refer to table 2. Narrow round, slit-like; oval and wide lumina are common but all other shapes are also present.
Figure S5: Reflected light micrograph of hemp stem. The numbers refer to table 1. Polygonal rounded shapes and oval cross-section shapes are common. All other shapes are present as well.
Figure S6: Reflected light micrograph of hemp stem: The letters refer to table 2. Narrow round lumina, oval and slit-like lumina are present as well as all other shapes.
Figure S7: Reflected light micrograph of nettle stem: The numbers refer to able 1. Oval and flattened cross-section shapes are very common, but polygonal and polygonal slightly rounded come often for as well as other shapes.
Figure S8: Reflected light micrograph of nettle stem: The letters refer to table 2. Lumina are mostly large and wide, slit-like, and flattened lumina show up as well as all other shapes.