# Twining things together: how functional approaches can help to understand the processing of fibres in the Palaeolithic

Veerle Rots and Sonja Tomasso


## Zusammenfassung

### Dinge miteinander verflechten: wie funktionale Ansätze helfen können, die Verarbeitung von Fasern im Paläolithikum zu verstehen

*Obwohl pflanzliche Fasertechnologien im prähistorischen Lebensalltag wahrscheinlich von entscheidender Bedeutung waren, insbesondere für die Herstellung von Bindungen, Schnüren und Textilien, sind sie wegen des schlechten Erhaltungsgrades nur unzureichend dokumentiert. Die vorliegende Studie ist ein erster Schritt zur Überbrückung dieser Lücke, indem sie die Faserverarbeitung mithilfe detaillierter experimenteller Versuche und systematischer Auswertung der mikroskopischen Gebrauchsspuren an Steinwerkzeugen untersucht. Damit wollen wir die archäologische Nachweisbarkeit solcher Aktivitäten erleichtern, auch wenn kein organisches Material erhalten ist. Wir konzentrieren uns auf eine Vielzahl von Pflanzenarten aus Feuchtgebieten, die für die Faserverarbeitung relevant sind, und berichten über die kontrollierten Experimente, die mit Steinwerkzeugen durchgeführt wurden. Wir diskutieren die Verschleißentwicklung und beleuchten, inwiefern Pflanzeneigenschaften wie Mineralgehalt und Härte zu diesem Prozess beigetragen haben könnten. Wir kommen zu dem Schluss, dass funktionelle Studien nützliche Erkenntnisse liefern können, um das Verständnis der Faserverarbeitung bei paläolithischen Völkern zu verbessern.*


**Schlagwörter** Gebrauchsspuren, Rückstände, Fasertechnologie, experimentelle Archäologie, Paläolithikum


## Summary

*Although plant-based fibre technologies were likely crucial in prehistoric life, especially for making bindings, cordage, and textiles, they remain poorly documented due to preservation issues. This study is a first step in bridging that gap by exploring fibre processing through detailed experimental work with systematic evaluation of the microscopic use-wear traces that develop on stone tools. As such, we aim to improve the archaeological recognition of such activities even when no organic material is preserved. We focus on a variety of wetland plant species relevant to fibre processing and report on controlled experiments conducted using stone tools. We discuss the wear formation and focus on how plant properties such as mineral content and hardness may have contributed to this process. We conclude that functional studies may provide useful insight to improve the understanding of fibre processing among Palaeolithic populations.*


**Keywords** Use-wear, residues, fibre technology, experimental archaeology, Palaeolithic

## Introduction

To manufacture clothing, Stone Age people could exploit both animal resources (e.g. hides, furs) and plant materials (e.g. fibres). Direct evidence for clothing is exceptionally rare due to the poor preservation chances of organic materials such as hides, fibres and textiles. Therefore, use-wear traces on stone tools are an important means of investigating when relevant raw materials were processed and whether the way in which these materials were processed reveals something about their possible role in the manufacture of clothing. For instance, preserved animal hides are virtually absent for the Palaeolithic period, but use-wear traces on stone tools indicate that hide-working activities predate the Upper Palaeolithic, with examples dating back to the early Middle Palaeolithic[1]. By contrast, signs of elaborate processing of animal hides (which suggest a use in clothing) only start to appear from the Upper Palaeolithic period onwards (Beyries/Rots 2008a; Beyries/Rots 2008b; Aleo et al. 2021). Similarly, we must reflect on the extent to which use-wear traces on stone tools can be helpful to infer the use of vegetal materials in clothing. A first step is to investigate how

1 E.g. Keeley 1980; Claud 2015; Rots et al. 2015; Venditti et al. 2022.

we can identify fibre processing, one of the so-called »invisible technologies« (Hurcombe 2014). Fibres are the basis for all clothing made from vegetal materials, but also for many other products (such as cordage) that are crucial in the daily lives of prehistoric hunter-gatherers. The ability to extract, process, and manipulate plant fibres into twine (and subsequently into ropes or textiles) represents a technological milestone in human evolution with important implications for tool hafting (Rots 2003), rope manufacture (Conard/Rots 2024) and associated aspects (e.g. transport, bags), subsistence (e.g. fishing nets), shelter construction, and, in addition, related technologies such as basketry (Hurcombe 2014). It is therefore fundamental to explore how functional studies can help to understand the invention and development of fibre-based technologies in the Palaeolithic.

Studying fibre-based technologies is methodologically complex, and furthermore, terminologies are not yet truly standardised. Attention has focused primarily on flax and wool textiles, and somewhat less on bast or leaf fibres and cordage. The main reason is that woven textiles are generally better preserved in burial contexts and wet environments, whereas materials such as cordage and basketry degrade more easily and are often only detected through indirect evidence, such as impressions in clay (Adovasio et al. 1999).

The definition of a ›textile‹ varies among researchers, with some scholars restricting the term to woven fabrics (e.g. Emery 1966), whereas others adopt a broader classification that includes perishable materials such as netting, twined fabrics, and even certain types of basketry (Harris 2014; Banck-Burgess et al. 2023). This hampers regional and chronological comparisons. Several initiatives have nevertheless been taken to move towards more standardised definitions, especially for wetland and arid environments where the chances of preservation are higher. Such studies have contributed to the establishment of a broader and more inclusive framework that recognises the diversity of fibre-based technologies beyond what may or may not be classified as a textile (Good 2001; Hurcombe 2014).

In this paper, we review existing evidence for plant processing, with a particular focus on fibre technology and ropemaking, since we regard these as precursor technologies to the production of textiles from plants. We address the main methodological challenges in studying these technologies from the perspective of a functional analysis of stone tools. We include the identification of fibre-processing tools, the limitations imposed by the lack of organic preservation, and the difficulties in distinguishing natural from anthropogenic fibre modifications. We also discuss how we have tried to overcome some of these challenges in recent experimental work. We do not address clothing production from animal products, since the technological trajectories are totally different, with hide processing being more readily identifiable through stone tool use-wear analysis (e.g. Rots/Williamson 2004; Beyries/Rots 2008a; Beyries/Rots 2008b).

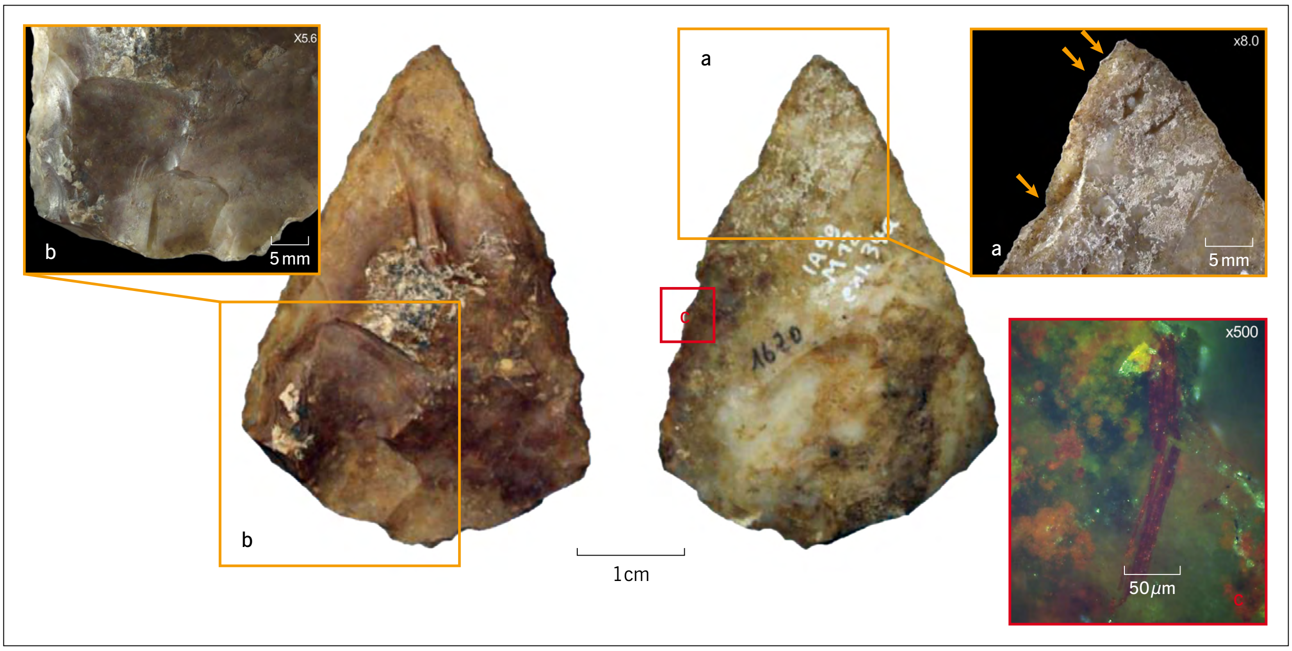
### *Research Context*

Vegetal resources have been exploited for technological purposes from early on, as illustrated by some exceptional finds, such as the unique wooden structural elements dating to 476 000 years ago recently recovered at Kalambo Falls, Zambia (Barham et al. 2023), which are the oldest examples to date, or the surprisingly rich set of wooden tools recovered from the 200 000- to 300 000-year-old site of Schöningen, Helmstedt District, Germany[2]. Also, other examples testify to the importance of the exploitation of vegetal resources[3]; these only provide a glimpse of the likely much broader range of wooden implements used by prehistoric hunter-gatherers.

While little direct evidence is preserved, cordage must also have played a crucial role for prehistoric people, not least for making all kinds of implements (e.g. stone tool hafting) or in construction (such as the tying of shelters or wooden structures). Indirect evidence for binding technology exists from as early as ~ 250 000 years ago in Europe (Rots 2013) and ~ 200 000 years ago in Africa (Rots/Van Peer 2006) and consists of wear traces demonstrating the use of bindings in stone tool hafting, even if the nature of the materials (animal or plant) remains unidentified. A more direct trace of the binding itself comes from the Middle Stone Age site of Ifri n'Ammar, Nador Province, Morocco, where one of the projectiles showed hafting wear in association with a ferruginised residual deposit that could be interpreted as the fossilised remains of a vegetal binding, thereby confirming the exploitation of plant fibres in connection with hafting during this period (Fig. 1; Tomasso 2024). Nevertheless, early evidence for rope or cordage remains is scarce and often disputed. A well-known example is the so-called »twisted fibre« from Abri du Maras, Dép. Ardèche, France (~ 46 ka), proposed as early evidence for cord making among Neanderthals (Hardy et al. 2020); this, however, is an interpretation we seriously question for multiple reasons. As shown in the published images, the fibre is clearly deposited on top of sediment, which suggests that it may represent contamination, and its singular nature does not convincingly support intentional twisting or deliberate use in cord making. The twist that can be observed represents a natural twist of a single fibre and does not show the combination of different strands of fibres in a Z- or S-twist to make string. Similarly, the twisted fibres reported from Ohalo II, Sea of Galilee, Israel (~ 19 ka) have not been conclusively identified as cordage (Nadel et al. 1994). After all, fibres are ubiquitous in prehistoric environments, and their adherence to artefacts or their presence in the sediments may result from natural processes. Detailed analysis is therefore required to demonstrate that the presence of fibres is due to an intentional process, ideally combined with clear signs of their manipulation or processing. The mere presence of a fibre, even if it may appear twisted, is therefore not sufficient evidence to argue for cordage.

2 Thieme 1997; Schoch et al. 2015; Conard et al. 2020; Conard/Rots 2024; Milks et al. 2023; Leder et al. 2024; Hutson et al. 2025.

3 E.g. Oakley et al. 1977; Thieme et al. 1985; Aranguren et al. 2018; Florindi et al. 2024; Carbonell/Castro-Curel 1992; Erič et al. 2018.



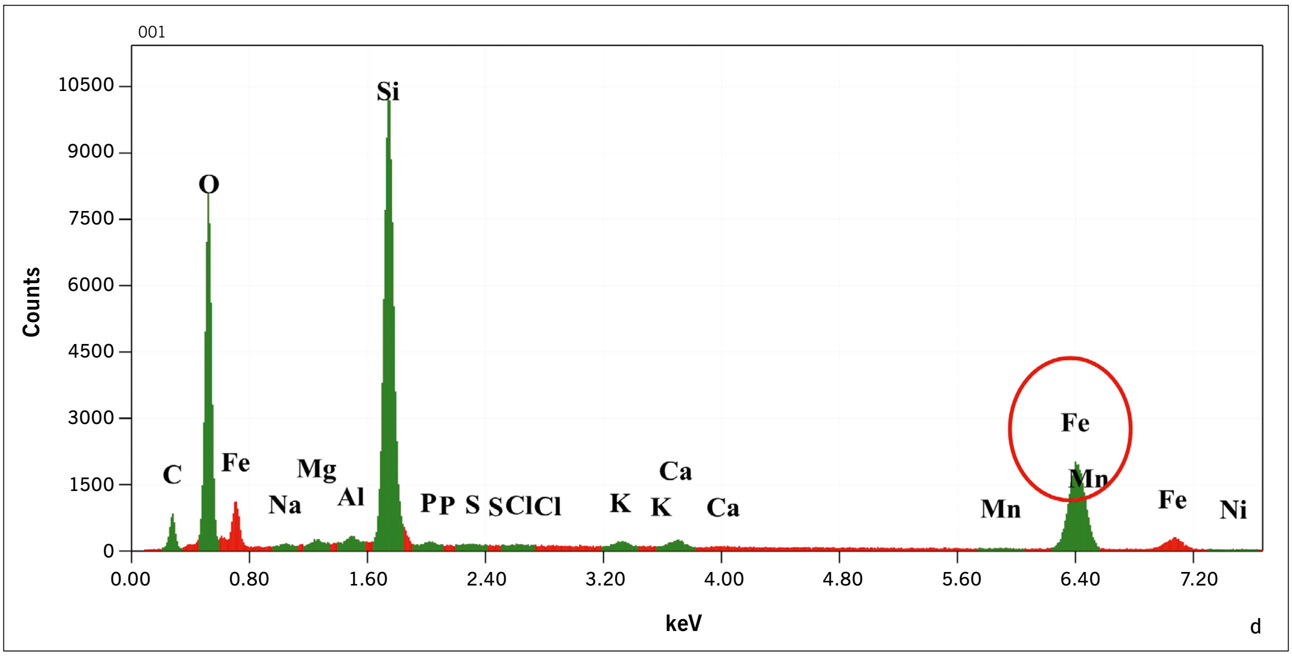




**Fig. 1a–d** Evidence of vegetal binding on a Middle Stone Age projectile from Ifri n'Ammar (Morocco); a macroscopic detail of the distal damage of the point, showing the bending-initiated scars with step-hinged and step-fissured terminations on the ventral face, all oriented in the same direction (x 8.0); b macroscopic detail of the possible intentional thinning on the proximal extremity with step-terminating scars on the dorsal face (x 5.6); c microscopic detail of the elongated ferruginised residue, under polarised light (x 500) and electron image detail of the same residue (x 400); d elemental spectrum of the ferruginised residue showing the significant peak of iron (Fe).

*Abb. 1a–d Nachweise für pflanzliche Umwicklung (Befestigung) an einem Projektil auf einem Middle Stone Age Projektil aus Ifri n'Ammar (Marokko). a Makroskopisches Detail der distalen Beschädigung der Spitze, mit den durch die Biegung entstandenen Negativen mit stufenförmig gelagerten und stufenförmig gesprungenen Enden auf der ventralen Seite, die alle in dieselbe Richtung weisen (x 8.0); b makroskopisches Detail der möglichen absichtlichen Verschlankung am proximalen Ende mit stufenförmig Enden der Abschlagsnegative auf der dorsalen Seite (x 5,6); c mikroskopisches Detail der länglichen ferruginisierten Residuen unter polarisiertem Licht (x 500) und Elektronenbilddetail desselben Rückstands (x 400); d Elementarspektrum der ferruginisierten Residuen, das ein signifikanten Peak von Eisen (Fe) zeigt.*

Early examples of fibre use, therefore, remain highly debated; however, more secure evidence is available for the later Upper Palaeolithic. Among the earliest direct examples of ropemaking in western Europe is a fossilised rope fragment made of twisted plant fibres from Lascaux, Dép. Dordogne, France, dated to approximately ~20 500 cal BP (Leroi-Gourhan 1982). Similarly, multiple interlaced or braided plant fibres from Santa Maira, Valencia Province, Spain, dated to 12 730–12 710 cal BP, represent the oldest directly dated evidence for the use of braided plant fibres in Europe (Aura Tortosa et al. 2020). Furthermore, exceptional preservation at sites like Nahal Hemar, near Mount Sodom, Israel, has revealed fragments of baskets, cords, linen yarns, and fabrics, demonstrating the technological complexity

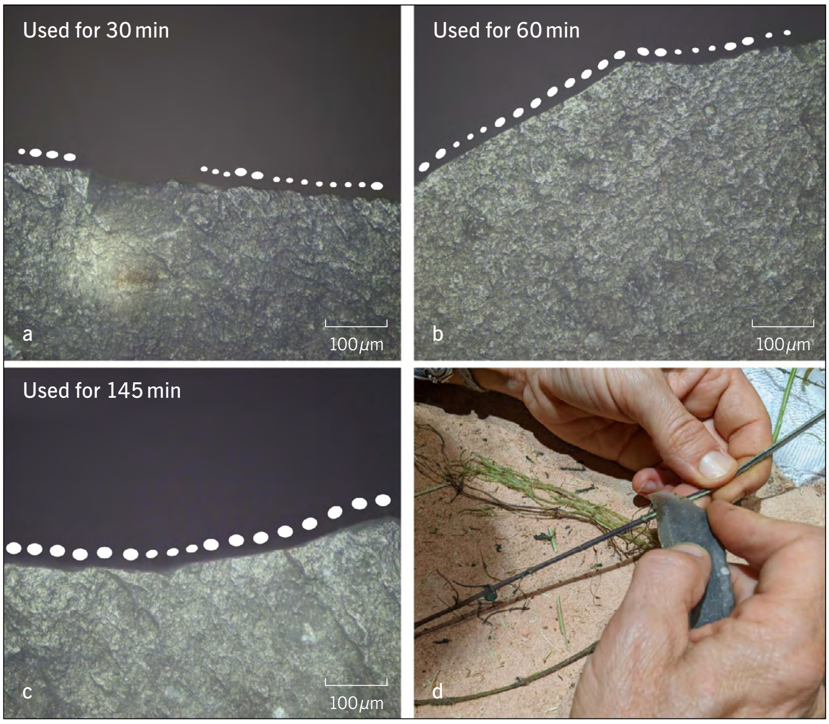



**Fig. 2a–d** Experimental fibre processing on fresh nettle stems illustrating the gradual development of wear patterns, with a) microscopic detail of the used edge of the experimental tool Exp110/106 after scraping nettle stems for 30 minutes, showing initial wear formation (× 200); b after 60 minutes of use, wear patterns remain weak with no significant change in development on the used edge of the tool Exp110/108 (× 200); c after 145 minutes, the edge exhibits slightly more pronounced rounding and polish, indicating progressive wear accumulation Exp 110/108 (× 200).

***Abb. 2a–d** Experimentelle Faserverarbeitung an frischen Brennnesselstängeln, die die allmähliche Entwicklung von Abnutzungsspuren veranschaulicht. a mikroskopisches Detail der verwendeten Kante des Versuchswerkzeugs Exp110/106 nach dem Schaben von Brennnesselstängeln für 30 Minuten, das die anfangende Verschleißbildung zeigt (× 200); b nach 60 Minuten Gebrauch bleiben die Abnutzungsspuren schwach, ohne signifikante Verschleißentwicklung an der verwendeten Kante des Werkzeugs Exp110/108 (× 200); c nach 145 Minuten zeigt die Kante eine etwas ausgeprägtere Abrundung und Politur, was auf eine fortschreitende Gebrauchsspurenbildung hinweist Exp 110/108 (× 200).*

and cultural significance of fibre use in the Neolithic Southern Levant (Shamir 2020).

More evidence is available for the beginning of the Holocene, probably because of improved general preservation conditions and a greater availability of fibre-producing plants, thanks to the spread of forests across northern and central Europe. Illustrative examples include a willow bast fishing net from Antrea (now Kamennogorsk) Leningrad Oblast, Russia (~ 8500–8200 cal BP; Carpelan 2008), plaited cords and net fragments from Friesack, Havelland District, Germany (~ 9100–7800 cal BP; Gramsch 1992), and needle-netted textiles from the submerged site of Tybrind Vig, Funen, Denmark (~ 7400–6000 cal BP; Andersen 2013). These finds illustrate both the technical sophistication and the deep-rooted tradition of fibre working among Mesolithic communities.

## Plant fibres and challenges in tracking Palaeolithic fibre working

Plant fibres are naturally derived from vascular plants (tracheophytes; Evert 2006), which have evolved specialised tissues providing structural support and flexibility. Their primary components, cellulose and lignin, determine their strength, durability, and elasticity, making them suitable for a wide range of technological applications. From a craft and technological perspective, plant fibres can be classified into hard and soft fibres, based on their physical, technical, and chemical properties. Plant fibres are categorised as hard fibres when they are extracted from monocotyledonous plant leaves and sedge stems. Such fibres are mainly used for cordage and basketry (Herrero Otal 2024). Soft fibres or bast fibres are extracted from the stalks of dicotyledonous plants like flax, hemp, and nettle. Such fibres require more intensive processing but are primarily used for textile production.

## What tools were used to manufacture and process fibres?

A key challenge in understanding fibre processing in the Palaeolithic is that it did not necessarily require the use of stone tools, as also shown by ethnographic observations and experiments. Fibres can be processed without tools, or with perishable organic tools such as wood, bone, or antler. Traditional societies commonly use wooden smoothers, weaving sticks, or spindles, all of which leave little to no archaeological traces. However, the use of grinding stones to pound or beat fibres to detach and soften them has been documented ethnographically, for example, in the case of Triodia grass *(Spinifex)* among Australian indigenous populations (Hayes et al. 2018). This implies that such applications could be visible archaeologically and identifiable through a combination of residue and use-wear analysis.

Even though direct evidence for organic tools is scarce, a few remarkable examples do exist. A notable case is a four-holed ivory artefact from the Aurignacian layers of Hohle Fels, Alb-Donau District, Germany, interpreted as a rope-making tool based on an integrated approach that includes wear and residue analysis, as well as experiments (Conard/Rots 2024). Other Upper Palaeolithic sites have also yielded relevant objects, including possible battens made from mammoth ribs and ivory, weaving sticks crafted from bird and mammal bones, as well as net gauges and spindles bearing use-wear patterns suggestive of textile or net-making activities (Soffer 2004). Bone needles are, of course, among the most convincing and recognisable tools associated with

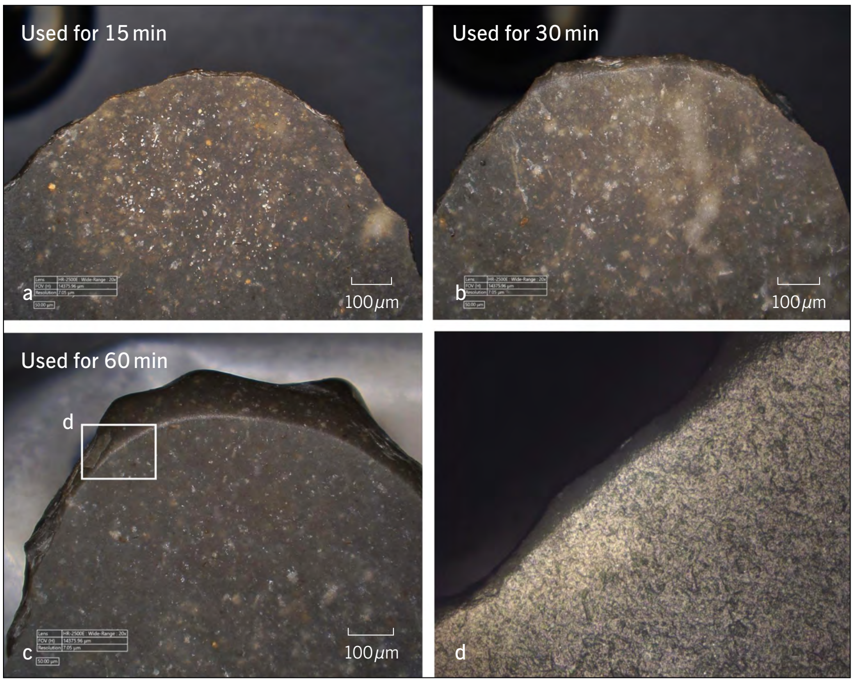



**Fig. 3a–d** Experimental scrapers used to scrape dry hide, illustrating the gradual development of wear patterns, with a) macroscopic detail of the used edge of the experimental tool Exp 56/21 after scraping dry hide for 15 minutes, showing initial edge rounding (×20); b after 30 minutes of use, a more pronounced edge rounding is visible on the scraper head Exp 56/23 (× 20); c after 60 minutes, the edge exhibits a very pronounced rounding, indicating progressive wear accumulation Exp 56/26 (× 20); d microscopic detail of the pronounced edge rounding of the experimental tool Exp 56/26 (× 200).

***Abb. 3a–d** Experimentelle Schaber zum Schaben von trockener Tierhaut, die die allmähliche Herausbildung von Abnutzungsspuren veranschaulichen. a Makroskopisches Detail der verwendeten Kante des experimentellen Werkzeugs Exp 56/21 nach 15 Minuten Schaben von trockener Tierhaut, das eine beginnende Kantenabrundung zeigt (× 20); b nach 30 Minuten Gebrauch ist eine ausgeprägtere Kantenabrundung am Schaberkopf Exp 56/23 sichtbar (× 20); c nach 60 Minuten weist die Kante eine sehr ausgeprägte Abrundung auf, was auf eine fortschreitende Verschleißbildung hinweist Exp 56/26 (× 20); d mikroskopisches Detail der ausgeprägten Kantenabrundung des Versuchswerkzeugs Exp 56/26 (× 200).*

fibre working and textiles or leather. Eyed needles appear from ~ 40 000 cal BP in Siberia, ~ 38,000 cal BP in the Caucasus, ~ 30 000 cal BP in East Asia, and by 26 000 cal BP in Europe (d'Errico et al. 2018; Gilligan et al. 2024). Numerous bone needles were recovered for Gravettian, Solutrean, and Magdalenian contexts; these often show eyelets, which typically associate them with sewing, although use in net-making, basketry, and fish-trap construction must also be considered (Cheval 2023). Evidence is clearly more abundant from the Mesolithic period onwards, such as a Mesolithic spatula-like tool made from a swan's ulna found at De Bruin, in Hardinxveld-Giessendam (South Holland Province, the Netherlands): it is decorated and perforated at one end. It shows use-wear consistent with fibre processing, such as plaiting or net-weaving, and experimental replication has confirmed its effectiveness (Van Gijn 2005). Noteworthy are also the bone awls found at the Middle Neolithic site of Schipluiden, South Holland Province, the Netherlands, on which microwear traces were observed that suggest their use in basket-making, possibly to secure willow bark fibres within a woven structure (Van Gijn 2008).

Altogether, these finds highlight the significant role of organic tools in fibre-processing technologies, yet their archaeological visibility remains limited due to preservation issues. Detailed analysis of flaked stone tools or stone implements alone will thus, by definition, underestimate the importance of fibre working and provide a partial view only. Moreover, even when stone tools are employed, it should be mentioned that fibre working places few demands on tool morphology or raw material, with simple blanks or waste products being perfectly suitable. This implies that they will only be detected archaeologically if the material selections for functional studies take this factor into account.

## Complexity of wear formation on stone tools

When stone tools are used for fibre processing, we can observe that the wear traces tend to form slowly and that traces often remain subtle, even after extensive use (Fig. 2). This contrasts sharply with dry hide processing, for instance, which produces very recognisable wear traces after a relatively short use (Fig. 3).

In addition, many variables influence the formation of wear traces in the case of fibre or plant processing. Firstly, moisture content plays a major role: plants collected during spring or from humid environments tend to produce better-developed polishes[4]. Secondly, factors such as the specific plant species worked, the season of harvesting, the nature of the task (e.g. stripping, softening, twining), and the use duration all play a role and may influence the characteristics and diagnostic aspect of the traces[5]. Wear formation is thus complex, and among all intervening variables, the plant species composition deserves special attention, since we note that differences in the biomineral content between plant species and different parts of the same plant introduce an additional layer of complexity (Tomasso et al. 2024).

4 Anderson-Gerfaud 1981; Astruc et al. 2003; Fullagar 1991; Hayden/Kamminga 1973; Ibáñez/Mazzucco 2021; Keeley 1980; Mazzucco et al. 2022; Unger-Hamilton 1983.

5 Evans et al. 2014; Gassin et al. 2013; Jensen 1994; Vaughan 1985.

6 Anderson-Gerfaud 1981; Fullagar 1991; Jensen 1994; Keeley/Newcomer 1977; Van Gijn 1990.

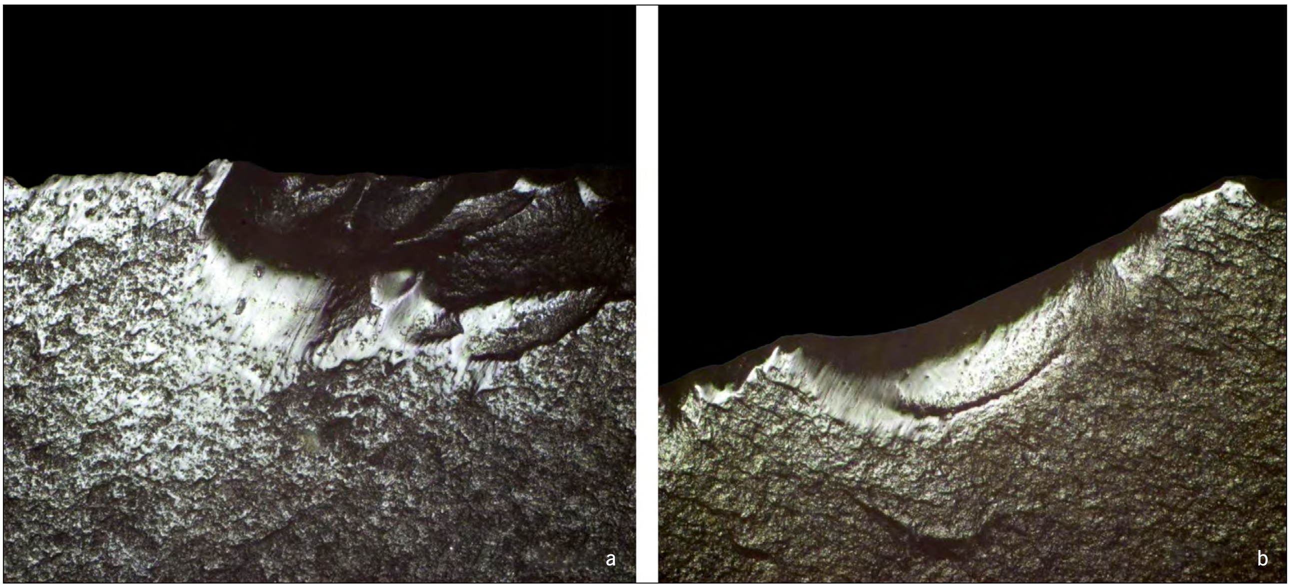



**Fig. 4a–b** Microscopic use-wear evidence of plant-working on Mesolithic flint artefacts from Beveren, East Flanders, Belgium; a–b detail of edge scarring combined with additional abrasion on the tool's working edge (× 200). These wear patterns align with previous observations from Northwest European Mesolithic contexts but exemplify the ongoing challenge of linking specific microwear traces to particular plant species or tasks.

***Abb. 4a–b** Mikroskopische Gebrauchsspuren von Pflanzenbearbeitung an mesolithischen Feuersteinartefakten aus Beveren, Ostflandern, Belgien; a–b Detail der Kantenvernarbung in Kombination mit zusätzlichem Abrieb an der Arbeitskante des Werkzeugs (× 200). Diese Abnutzungsmuster stimmen mit früheren Beobachtungen aus nordwesteuropäischen mesolithischen Kontexten überein, sind aber ein Beispiel für die anhaltende Herausforderung, spezifische Mikroabnutzungsspuren mit bestimmten Pflanzenarten oder Aktivitäten in Verbindung zu bringen.*

## Diversity in plant species composition

A broad range of plant species is available for fibre production, and each species differs in its biomineral composition, which may affect wear formation on stone tools. The effect of silica, present as phytoliths, has been most extensively studied and is known for its abrasive characteristics[6]. The silica content varies widely between species, with high-silica plants, such as *Equisetum* and wetland grasses, producing stronger polish than low-silica species, like legumes (Jensen 1994). While these differences can present advantages for distinguishing among processed plants, it remains very challenging on the basis of wear traces alone and generally requires the integration of residue analysis (Pearsall 1994; Piperno 2006; Raven 1983).

Other biominerals, such as calcium oxalates, are comparatively underexplored (but see Tomasso et al. 2024), and more comprehensive experiments are needed to systematically evaluate the impact of a broad spectrum of plant properties. Early experimental work has mostly focused on wear formation for the general category of plants or specific cases like sickle gloss[7], while more recent studies have expanded towards a more detailed understanding of cereal harvesting (Anderson 1999; Ibáñez et al. 2008; Mazzucco et al. 2016), fibre production (Caspar et al. 2007; Hurcombe 1994), and the relationship between tool form and plant processing[8].

However, it remains an important challenge that many experiments involve small sample sizes and do not always document variables like plant part worked, species, working environment, and harvesting season in sufficient detail. The reference framework, therefore, remains fragmented, which complicates archaeological interpretations[9]. Experiments with long use durations remain rare, with cereal processing as a notable exception[10]. Given the importance of long usage for diagnostic wear to form and the possibility of equifinality between certain activities, the reference framework urgently needs to be elaborated upon.

## Ambiguities in plant polish formation on stone tools

Identifying plant-working activities based on microwear traces remains a challenge[11]. Several Final Palaeolithic and Mesolithic flint artefacts from sites across Northwest Europe, including regions such as Denmark, Britain, and France, have been shown to exhibit distinctive smooth, bright polishes that are typically attributed to the processing of siliceous plant fibres[12]. However, the specific plant species or the nature of the activity remain uncertain because the variation in polish formation is still insufficiently documented, making it difficult to establish a reliable link between specific use-wear traces and a particular (range of) task(s) (Fig. 4).

7 Anderson 1980; Curwen 1930; Curwen 1935; Fullagar 1991; Gassin 1994.
8 Beugnier/Crombé 2007; Gassin 1994; Guéret et al. 2014; Osipowicz 2019; Sobkowiak-Tabaka/Kufel-Diakowska 2019; Little/Van Gijn 2017.
9 Beugnier/Crombé 2005; Gassin et al. 2013; Little/Van Gijn 2017; Sobkowiak-Tabaka/Kufel-Diakowska 2019.
10 Anderson-Gerfaud 1992; Ibáñez/Mazzucco 2021; Mazzucco et al. 2022; Van Gijn 1990.
11 E.g. Little/Van Gijn 2017, Osipowicz 2019; Sobkowiak-Tabaka/Kufel-Diakowska 2019.
12 Jensen 1994; Hurcombe 2008; Gassin et al. 2013; Guéret 2013; Little/Van Gijn 2017.

**Fig. 5a–d** Examples of plant-working experiments: a scutching dry flax; b scraping bark of a hazelnut branch *(Corylus avellana)*; c cutting a branch bark of *Salix alba*; d cutting a branch of *Salix alba*.

***Abb. 5a–d** Beispiele für Pflanzenbearbeitungsexperimente: a Hecheln von trockenem Flachs; b Abschaben der Rinde eines Haselnusszweiges* (Corylus avellana)*; c Schneiden der Zweigrinde von* Salix alba*; d Schneiden eines Zweiges von* Salix alba.

Another illustrative example of this complexity is what has been termed ›Polish 23‹, a well-known but poorly understood polish type. Recognised from early on in use-wear studies (e.g. Caspar et al. 2005), it is characterised by a combination of features suggestive of both plant and animal contact. Indeed, one surface generally exhibits wear traces reminiscent of hide-working, including edge rounding associated with a rough and dull polish, and striations perpendicular to the edge, whereas the opposite surface shows a bright, smooth polish that is reminiscent of plant-working. Reproducing this double characteristic experimentally has been challenging. This Polish 23 is nevertheless well-documented from the Final Palaeolithic onwards while appearing relatively frequently in early Neolithic assemblages (Caspar et al. 2005). A possible link with flax fibre processing was proposed on the basis of a range of experimental studies[13], but these interpretations have never been entirely satisfactory because the exact wear characteristics have remained difficult to reproduce. This is likely due to insufficient knowledge regarding the impact of variables such as plant species, plant condition (fresh, soaked, or dry), and the use of additives.

## Possibilities in terms of methodological approach: rationale

Building on the efforts of other researchers, we have tried to advance the understanding of fibre processing on the basis of an integrated approach that combines substantial experimental work, detailed wear and residue analysis, a botanical reference library, and an analysis of the biomineral composition of the plants (see also Tomasso et al. 2024). We hope that such an approach will improve insight into the formation process of wear traces and how this process is impacted by varying plant compositions. We observe that the abundance of silica minerals and/or calcium oxalates differs between plant species, but also between different parts of one and the same plant, which emphasises the importance of the biomineral composition of the plant (parts) for adequately understanding use-wear formation (Tomasso et al. 2024) and artisanal activities. A more systematic integration of residue analysis is also important, as the recovery of residual plant fragments on the stone tool surfaces may help to identify the plant species. At the same time, experimental programs need to cover the broad range of possible artisanal plant working tasks and include sufficiently long and realistic use durations to guarantee a better understanding of the wear formation process and possible equifinality between activities or plant species. The resulting reference framework will be more robust and serve as a more reliable reference against which archaeological assemblages can be compared.

## Results from recent experiments and functional analyses

Recently, we have invested efforts in developing a large-scale experimental program within the rationale presented above, and we include some results from the first phase of this programme here. We emphasise that this initial phase was exploratory in nature and aimed to enhance our knowledge of plant wear formation when processing wetland plants (for more details, see Tomasso et al. 2024). The programme included the creation of a reference collection of plants available in Northwestern European wetland ecosys-

13 E.g. Caspar et al. 2005; Beugnier/Crombé 2005; Beugnier/Crombé 2007; Osipowicz 2019.

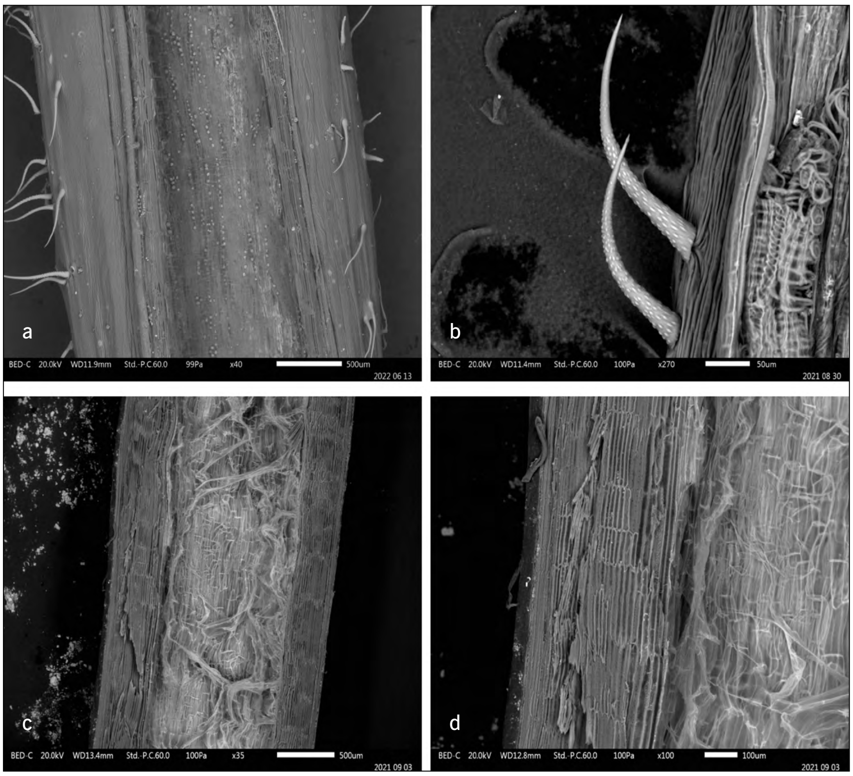



**Fig. 6a–d** SEM-EDS analysis of botanical samples: a–b silica minerals present in the trichomes of nettle *(Urtica dioica)*; c–d virtual absence of biominerals present in the stem of flax *(Linum usitatissimum)*.

***Abb. 6a–d*** *REM-EDS-Analyse botanischer Proben: a–b Kieselsäuremineralien in den Trichomen der Großen Brennnessel* (Urtica dioica)*; c–d weitgehende Abwesenheit von Biomineralien im Stengel des Flachses* (Linum usitatissimum).

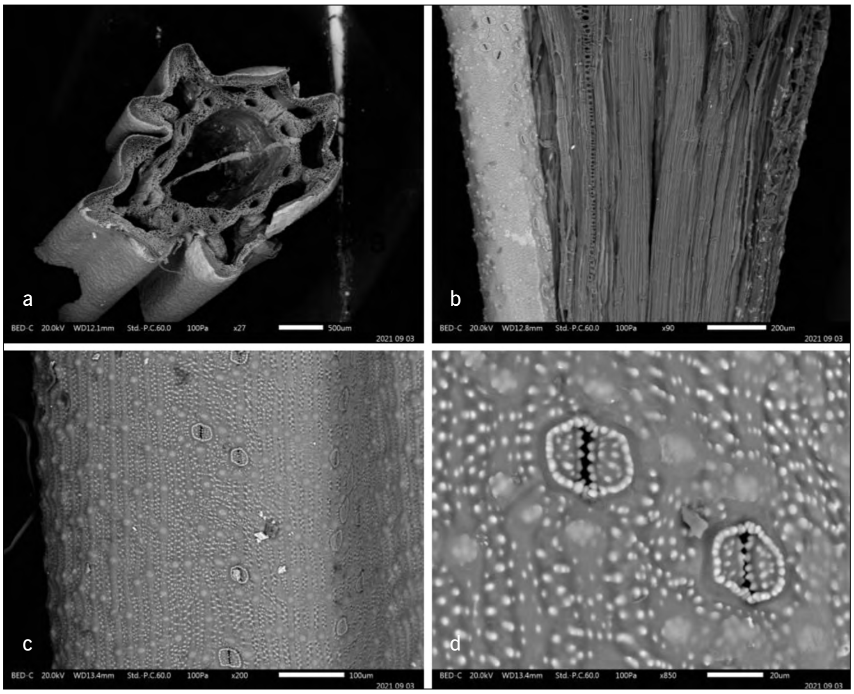



**Fig. 7a–d** SEM-EDS analysis of botanical samples, showing the high amount of silica located on the epidermal surface of horsetail *(Equisetum telmateia)*, with a) detail of the transversal section of the stem and; b–d the longitudinal section of the same part of the stem.

***Abb. 7a–d*** *REM-EDS-Analyse botanischer Proben, die den hohen Anteil an Kieselsäure auf der epidermalen Oberfläche des Schachtelhalms* (Equisetum telmateia) *zeigt, mit a) Detail des Querschnitts des Stängels und; b–d Längsschnitt desselben Teils des Stängels.*

tems and a set of plant processing experiments (Fig. 5) to improve our understanding of plant wear formation within a controlled setting. We specifically sought to explore the impact of the biomineral composition of the plants (Fig. 6–8; i.e. silica and calcium oxalates) on wear trace formation and to contribute to a more comprehensive reference framework to facilitate the identification of plant-related wear traces in archaeological contexts. Attention was also devoted to the influence of use duration and working angle.

The result is a reference collection of tools used to process 15 wetland plant species (Tab. 1) for durations of up to 265 minutes and with consistent motions to process and clean plant parts (Tomasso et al. 2024). For each of these, we systematically tested how differences in silica and calcium oxalate content affect the wear formation process.

Tools were analysed for wear patterns using multiple microscopic techniques, including optical microscopy (stereomicroscopes, metallurgical microscopes) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS). Wear attributes such as polish distribution, topography, and edge damage were systematically documented, and hierarchical clustering analy-

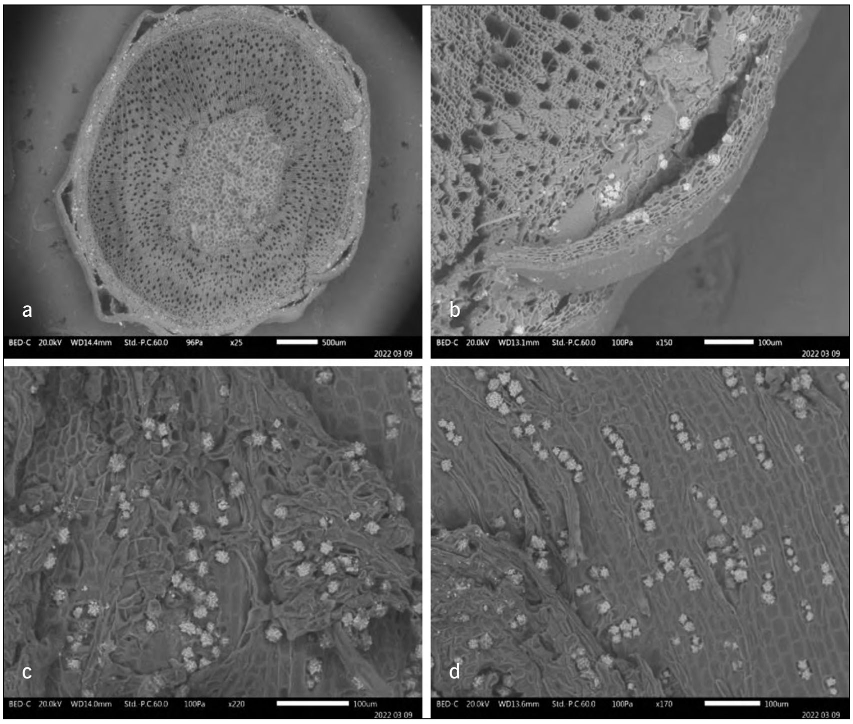



**Fig. 8a–d** Location of calcium oxalate crystals shown in a–b (transversal section) in the epidermis of willow *(Salix alba)*; c–d longitudinal section showing a detail of the calcium oxalate crystals with a druse morphology.

***Abb. 8a–d** Lage der Kalziumoxalatkristalle in a und b (Querschnitt) in der Epidermis der Weide* (Salix alba)*; c–d Längsschnitt, der ein Detail der Kalziumoxalatkristalle mit einer Drusenmorphologie zeigt.*

**Tab. 1** Overview of the 15 wetland plant species used in the first phase of the experiment.

***Tab. 1** Übersicht über die 15 Feuchtgebietspflanzenarten, die in der ersten Phase des Experiments verwendet wurden.*

| Plant species | Family | Plant part | Calcium oxalate (CO) | Silica (Si) |
|---|---|---|---|---|
| *Equisetum Arvense* | Horsetail | stem | absent | present |
| *Equisetum Telmateia* | Horsetail | branch | absent | present |
| *Dryopteris Filix-Mas* | Male Fern | stem | absent | absent |
| *Typha latifolia* | Bulrush | leaf | present | absent |
| | | stem | absent | present |
| *Phalaris arundinacea* | Reed canary grass | leaf | absent | present |
| | | stem | absent | present |
| *Urtica dioica* | Stinging nettle | stem | present | present |
| *Dactylis glomerata* | Cock‘s-foot | stem | absent | present |
| *Rubus (fruticosus)* | Blackberry | stem | present | absent |
| *Corylus (avellana)* | Common hazel | branch | present | absent |
| *Alnus (glutinosa)* | Black alder | branch | present | absent |
| *Tilia cordata* | Small-leaved lime | branch | present | absent |
| *Quercus cerris* | Turkey Oak | branch | present | absent |
| *Salix alba* | White willow | branch | present | absent |
| *Ulmus* sp. | Elm | branch | present | absent |
| *Betula* | Birch | bark | present | absent |

sis was employed to identify patterns in wear variability (see Tomasso et al. 2024 for more details). We were able to demonstrate that differences in polish formation are primarily explained by the significant difference in hardness between silica and calcium oxalate crystals, with plant silica being up to 170 times harder. Secondly, silica density and overall material hardness appear to influence the degree of abrasion, regardless of whether the plant is herbaceous or woody. Moreover, use duration proves to play a secondary role in polish development when processing wetland plants compared to the biochemical and physical properties of the plant itself. Knowledge of the plant properties is thus essential for a reliable reference to be used when examining archaeological tools for evidence of plant processing.

This initial phase of the experimental program highlighted the multifaceted nature of plant wear formation and the influence of variables related to the plant and the activity. It provides a good basis for the continued development of existing references to consolidate archaeological interpretations.

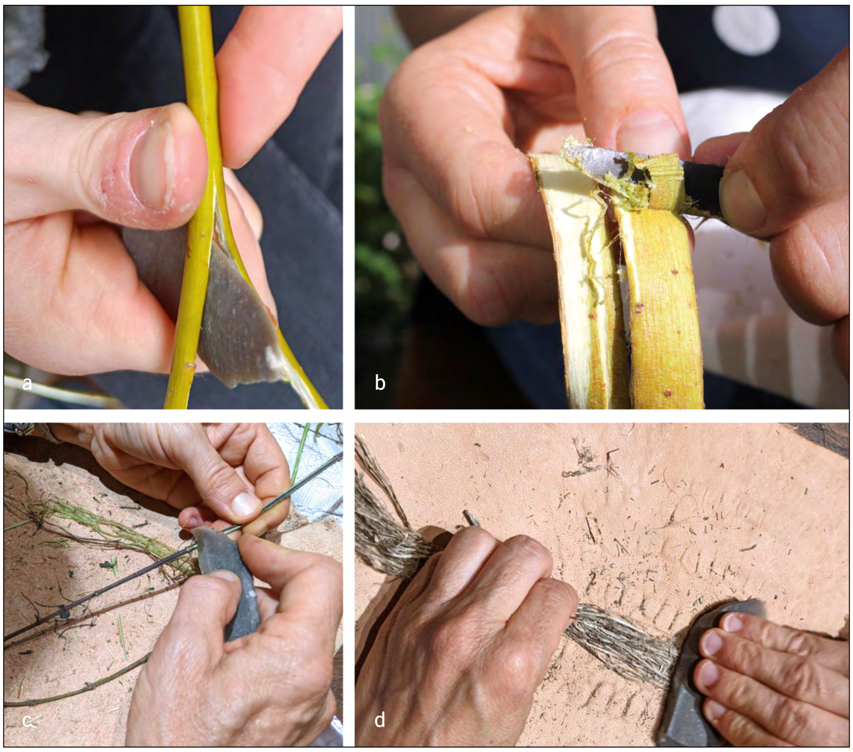



**Fig. 9a–d** Experimental tools used in fibre processing. This subset of experiments focused on scutching, breaking, and scraping plant stems to extract fibres: a splitting willow *(Salix alba)*; b cleaning the cambium of willow *(Salix alba)*; c–d scraping nettle *(Urtica dioica)*.

***Abb. 9a–d** Experimentelle Werkzeuge, die bei der Verarbeitung der Fasern verwendet wurden. Diese Untergruppe von Experimenten konzentrierte sich auf das Hecheln, Brechen und Schaben von Pflanzenstängeln zur Gewinnung von Fasern: a Spaltung von Weide* (Salix alba)*; b Reinigung des Kambiums von Weide* (Salix alba)*; c–d Schaben von Großer Brennnessel* (Urtica dioica).

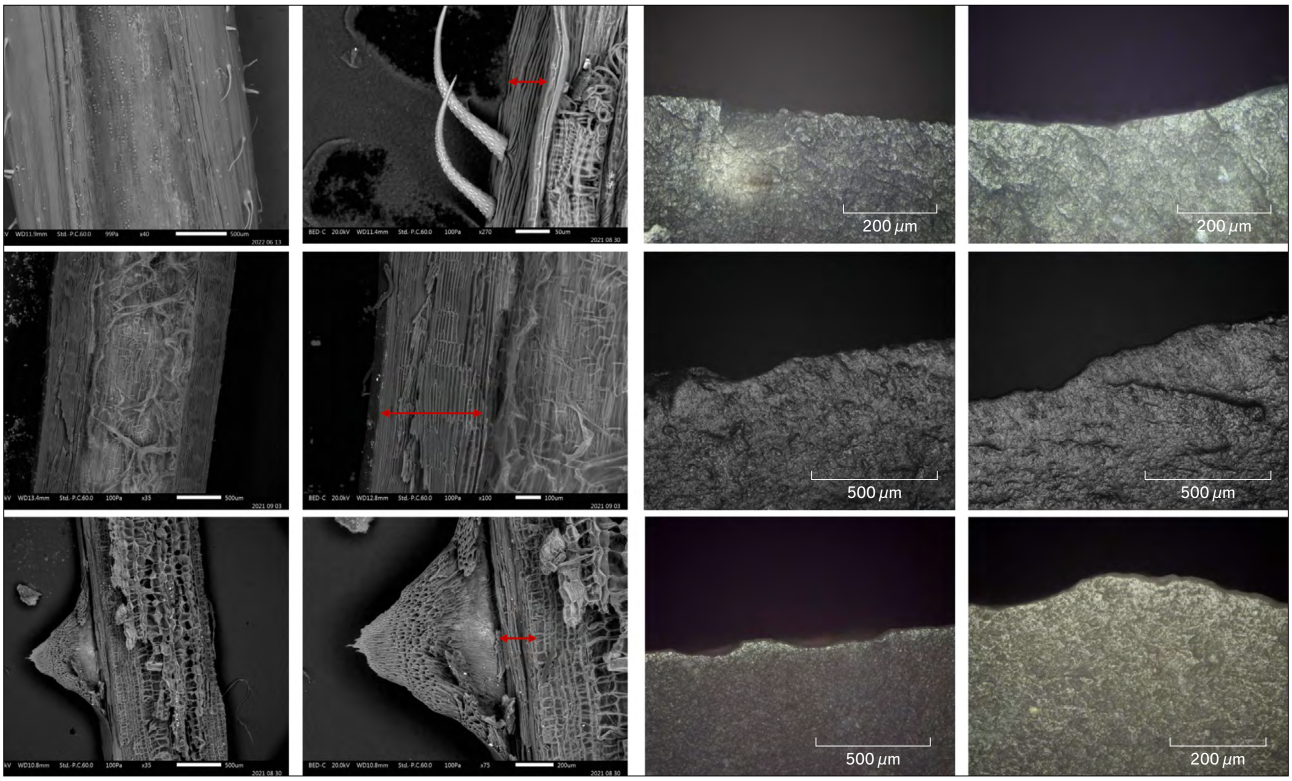



**Fig. 10** Development of wear patterns on the ventral edge of experimental tools due to increasing use duration, and different plants used with the aim to extract fibres. From top to bottom: tools used to process nettles show weak edge rounding and minimal polish on the used edge; tools used for scutching flax show distinct striations and more pronounced edge rounding; tools used to scrape bramble demonstrate very well-developed edge rounding and polish.

***Abb. 10** Entwicklung von Abnutzungsspuren an der ventralen Kante von Versuchswerkzeugen aufgrund zunehmender Nutzungsdauer und verschiedener Pflanzen, die zur Gewinnung von Fasern verwendet wurden. Von oben nach unten: Werkzeuge, die zur Bearbeitung von Brennnesseln verwendet wurden, zeigen eine schwache Kantenabrundung und eine minimale Politur an der benutzten Kante; Werkzeuge, die zum Hecheln von Flachs verwendet wurden, zeigen deutliche Rillen und eine ausgeprägtere Kantenabrundung; Werkzeuge, die zum Schaben von Dornenstrauch verwendet wurden, zeigen eine sehr gut entwickelte Kantenabrundung und Politur.*

| Used part | Angle of work | Worked material | Plant part | Worked material details | Action | Duration | Prehen-sile mode |
|---|---|---|---|---|---|---|---|
| right edge | 90° | *Urtica dioica* | stem | fresh | cutting | 20' | hand-held |
| left edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right proximal part | 70° | *Linum usitatissimum* | stem | dry | scutching | 60' | hand-held |
| left edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right edge | 80–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| left edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right edge | 80–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| left edge | 75–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| left edge | 70–50° | *Linum usitatissimum* | stem | dry | scutching | 30' | hand-held |
| right edge | 80–50° | *Linum usitatissimum* | stem | dry | scutching | 60' | hand-held |
| left edge | 80–45° | *Linum usitatissimum* | stem | dry | scutching | 60' | hand-held |
| left edge | 90° | *Urtica dioica* | stem | fresh | cutting | 12' | hand-held |
| right edge | 90° | *Salix alba* | branch | fresh | cutting | 60' | hand-held |
| right edge | 90° | *blackberry wood* | branch | fresh | cutting | 60' | hand-held |
| facet | 80–45° | *Linum usitatissimum* | stem | dry | scutching | 60' | hand-held |
| facet and right edge | 80–45° | *Linum usitatissimum* | stem | dry | scutching | 60' | hand-held |
| facet and left edge | 80–45° | *hemp* | stem | dry | scutching | 60' | hand-held |
| facet and left edge | 80–45° | *hemp* | stem | dry | scutching | 60' | hand-held |
| left edge | 90° | *Amadou* | bark | dry | cutting | 60' | hand-held |
| left edge | 90° | *Amadou* | bark | dry | cutting | 5' | hand-held |
| left edge | 90° | *Amadou* | bark | dry | cutting | 15' | hand-held |
| right edge | 90° | *Amadou* | bark | dry | cutting | 30' | hand-held |
| right edge | 90° | *Amadou* | tubes | dry | cutting | 60' | hand-held |
| right edge | 90° | *Amadou* | tubes | dry | cutting | 5' | hand-held |
| left edge | 90° | *Amadou* | tubes | dry | cutting | 15' | hand-held |
| left edge | 90° | *Amadou* | tubes | dry | cutting | 30' | hand-held |
| right distal edge | 90° | *Equisetum Arvense* | stem | fresh | cutting | 30' | hand-held |
| right edge | 90° | *Dryopteris Filix-Mas* | stem | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Rubus (fruticosus)* | stem | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Corylus (avellana)* | branch | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Alnus (glutinosa)* | branch | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Rheum × hybridum (?)* | branch + leaf | fresh | cutting | 12' | hand-held |
| distal part | 90° | *Typha* sp. | leaf | fresh | cutting | 30' | hand-held |
| right edge | 90° | *Rubus (fruticosus)* | stem | fresh | cutting | 60' | hand-held |
| right edge | 90° | *Typha* sp. | stem | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Hematite* | / | dry | cutting | 30' | hand-held |
| right edge | 90° | *Salix alba* | branch | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Tilia* sp. | branch | fresh | cutting | 30' | hand-held |
| right edge | 90° | *Tilia* sp. | branch | fresh | cutting | 10' | hand-held |
| right edge | 90° | *Sandstone* | / | processed fresh surface | cutting | 30' | hand-held |
| right edge | 90° | *Equisetum Telmateia* | branch | fresh | cutting | 5' | hand-held |

| Used part | Angle of work | Worked material | Plant part | Worked material details | Action | Duration | Prehensile mode |
|---|---|---|---|---|---|---|---|
| left edge | 90° | *Equisetum Telmateia* | branch | fresh | cutting | 10' | hand-held |
| right edge | 90° | *Equisetum Telmateia* | branch | fresh | cutting | 30' | hand-held |
| left edge | 80–45° | *Equisetum Telmateia* | branch | fresh | scraping | 10' | hand-held |
| left edge | 90° | *Oak Quercus* | branch | fresh | cutting | 20' | hand-held |
| left edge | 90° | *Oak Quercus* | branch | fresh | cutting | 10' | hand-held |
| right edge | 45–90° (removing bark/ splitting) | *Salix alba* | branch | fresh | removing bark + splitting | 60' | hand-held |
| left edge | 90° | *Salix alba* | branch | fresh | splitting | 60' | hand-held |
| right edge | 90° | *Rubus (fruticosus)* | branch | fresh | removing blackberry spines | 60' | hand-held |
| left edge | 90° | *Rubus (fruticosus)* | branch | fresh | splitting | 60' | hand-held |
| right edge | 45° | *Salix alba* | branch | fresh | cleaning the cambium | 60' | hand-held |
| left edge | 90° | *Salix alba* | branch | fresh | hollowing branches | 60' | hand-held |
| right edge | 45° | *Salix alba* | branch | fresh | removing bark | 60' | hand-held |
| right edge | 80–45° | *Corylus (avellana)* | branch | fresh | scraping the bark | 60' | hand-held |
| left edge | 90° | *Tilia* sp. | branch | fresh | cutting bark for removal | 60' | hand-held |
| right edge | 90° | *Tilia* sp. | branch | fresh | cutting bark for removal | 265' | hand-held |
| right edge | 90° | *Tilia* sp. | branch | fresh | cutting bark for removal | 15' | hand-held |
| left distal edge | 90° | *Ulmus* sp. | branch | fresh | cutting bark for removal | 25' | hand-held |
| right edge | 45° | *Salix alba* | branch | fresh | removing outer bark from inner bark | 60' | hand-held |
| right edge | 90° | *Phalaris arundinacea* | leaf | fresh | splitting leaves in small fibres | 30' | hand-held |
| right edge | 45–90° | *Birch bark* | bark | fresh | cutting the bark | 30' | hand-held |
| left edge | 90° | *Phalaris arundinacea* | stem | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Urtica dioica* | stem | fresh | cutting | 30' | hand-held |
| left edge | 90° | *Dactylis glomerata* | stem | fresh | cutting | 30' | hand-held |

**Tab. 2** Overview of experimental conditions and materials used in plant processing experiments.

***Tab. 2*** *Übersicht über die Versuchsbedingungen und die bei den Pflanzenverarbeitungsexperimenten verwendeten Materialien.*

A subset of the experiments focused specifically on fibre processing (Tab. 2). For instance, when tools were used for scutching, i.e. breaking and scraping plant stems to extract fibres (Fig. 9), wear from this activity proved to develop particularly slowly, both in terms of macroscopic edge damage, microscopic edge rounding, and polish formation. Among the tested plants, bramble produced the most pronounced wear, followed by flax, and then nettle (Fig. 10). This hierarchy aligns with our general findings: bramble, being the hardest of the three and the richest in calcium oxalate crystals, resulted in greater abrasion of the stone tool edges. Plant hardness and biomineral composition are thus key drivers in wear formation when activities are similar.

In an additional exploratory experiment, we tested the efficiency of organic versus stone tools for extracting fibres from dry flax using a scutching motion. The tools included a retouched flint flake and a wooden knife, the latter modelled after so-called ›weaving swords‹ known from early Neolithic sites such as La Marmotta (Mineo et al. 2023). Scanning electron microscopic (SEM) analysis revealed clear differences in the condition of the fibres processed with each tool. The fibres processed with the flint flake proved significantly more fragmented and broken com-

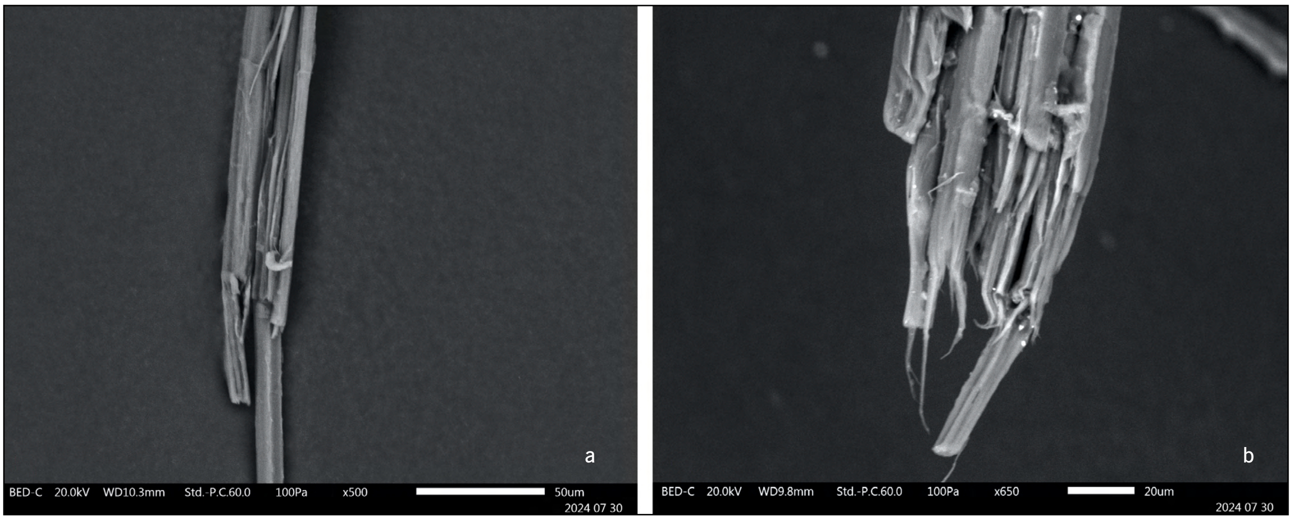



**Fig. 11a–b** SEM images of flax fibres processed using different tools: a flax fibres remain largely intact when processed with a wooden tool, indicating a gentler separation; b flax fibres show significant fragmentation after processing with a flint tool.

***Abb. 11a–b*** *REM-Bilder von Flachsfasern, die mit verschiedenen Werkzeugen bearbeitet wurden: a Flachsfasern bleiben bei der Bearbeitung mit einem Holzwerkzeug weitgehend intakt, was auf eine sanftere Trennung hindeutet; b Flachsfasern zeigen eine deutliche Fragmentierung nach der Bearbeitung mit einem Feuersteinwerkzeug.*

pared to those processed with the wooden tool. Indeed, the sharp edge of the stone tool tended to damage the fibres, producing sharp break points and splintered ends, whereas the wooden implement allowed for the separation of the fibres without breakage (Fig. 11). This observation confirms that stone may not have been the preferred raw material for tools used when working fibres.

Future phases of this experimental programme will focus on an exploration of fibre processing techniques, with particular attention to tool efficiency, wear development, and the preservation of fibre integrity across a broader range of plant species and tool types.

## Conclusions

In the absence of direct evidence for fibre processing, functional studies of stone tools (that include use-wear and residues) combined with experimental programmes are essential tools for better recognising plant processing and craft activities among prehistoric groups. While functional studies have already contributed significantly to our understanding of plant processing in the Palaeolithic, fibre processing, ropemaking, and clothing production remain the most challenging topics to address. As a result, most evidence remains indirect, even for the Upper Palaeolithic. An important caveat is that fibre working does not necessarily require stone tools and may have relied on perishable organic implements, meaning that its archaeological visibility is limited, with stone tools only being able to provide a very partial view of these technologies while also necessitating a continued investment in improving our understanding of fibre-related wear traces.

Different lines of evidence have shown that Neanderthals had an in-depth knowledge of various plants and exploited them for both subsistence and tool manufacturing purposes. For modern humans, the issue is far less debated, and while early evidence is still very sparse, expertise has been assumed. All evidence combined, it still seems that fibre processing has a very long history and that it is relevant to continue to invest in improving how these artisanal activities can be recognised archaeologically. We have demonstrated that this task is challenging due to the broad range of exploitable plants and tasks; however, an approach that integrates detailed experimental work with use-wear and residue analyses, as well as the elaboration of botanical reference libraries and trace libraries, appears promising. Initial results highlight the important role of the biomineral composition of plants in wear formation. This research will continue to be built upon in the future, and, hopefully, this approach will lead to a more robust reference framework and a better understanding of the long history of fibre processing among prehistoric hunter-gatherer groups.

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## Source of figures

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| 1–5 | S. Tomasso, Liège |
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## Addresses

Prof. Dr. Veerle Rots
FNRS Research Director
TraceoLab
University of Liège
Place du 20-août 7 (Bât. A4)
4000 Liège
Belgium
Veerle.rots@uliege.be
ORCID: 0000-0002-6404-3160

Dr. Sonja Tomasso
TraceoLab
University of Liège
Place du 20-août 7 (Bât. A4)
4000 Liège
Belgium
stomasso@uliege.be
ORCID: 0000-0002-0465-4808