Fibre-based technologies of the Last Hunter-gatherers and First Farmers in southern Europe: Baskets, cords and footwear from the Cueva de los Murciélagos site (Albuñol, Granada)

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Zusammenfassung

Faserbasierte Technologien der letzten Jäger und Sammler und der ersten Bauern in Südeuropa: Körbe, Schnüre und Schuhwerk aus der Cueva de los Murciélagos (Albuñol, Granada)

Materielle Kultur aus organischen Komponenten bietet unschätzbare Einblicke in die handwerklichen Fähigkeiten, technologischen Innovationen und Anpassung an die vorhandenen Ressourcen prähistorischer Gesellschaften. Ihre Vergänglichkeit hat jedoch oft unser Verständnis ihrer vielfältigen und komplexen Anwendungen eingeschränkt. Fundplätze mit außergewöhnlichen Erhaltungsbedingungen bieten einzigartige Möglichkeiten für eingehende Studien der materiellen organischen Kultur. Ein solches Beispiel ist die Fundstätte Cueva de los Murciélagos, Provinz Granada, im Süden der Iberischen Halbinsel, die einige der ältesten, umfangreichsten und am besten erhaltenen faserbasierten Objekte der letzten Jäger und Sammler und der ersten Ackerbaugemeinschaften in Südeuropa geliefert hat. In dieser Studie werden die organischen faserbasierten Materialien – sowohl pflanzlicher als auch tierischer Herkunft – durch eine Multi-Proxy-Untersuchung mithilfe von Mikroskopie und biomolekularen Methoden neu untersucht. Die Ergebnisse zeigen die Verwendung von Espartograsblättern und Sehnen von drei verschiedenen Tierarten zur Herstellung von Grabbeigaben und Alltagsgegenständen. Die Funde der Ausgrabungstätte beleuchten das, was in der Archäologie als ›unsichtbare Technologien‹ bezeichnet wird, und erweitert unser Verständnis für die Erfindungsgabe und den Einfallsreichtum dieser früh- und mittelholozänen Gesellschaften.

Schlagwörter Organische Materialien, Pflanzenfasern, Tierische Sehnen, Archäobotanik, Biomolekulare Analyse

Summary

Material culture made of organic components provides invaluable insights into the craftsmanship, technological innovation and resource adaptations of prehistoric societies. However, its perishable nature has often limited our understanding of its diverse and complex applications. Sites with exceptional preservation conditions offer unique opportunities for in-depth studies of perishable material culture. One such example is the Cueva de los Murciélagos site, Granada Province, in southern Iberia, which has yielded some of the oldest, most extensive and best-preserved fibre-based objects known from the last hunter-gatherer and first farming communities in southern Europe. This study re-examines the organic fibre-based materials – of both plant and animal derivation – through a multi-proxy investigation using microscopy and biomolecular methods. The results reveal the use of esparto grass leaves and sinews from three different animal species to produce funerary and everyday objects. The site's discoveries illuminate what have been termed ›invisible technologies‹ in archaeology, broadening our understanding of the ingenuity and resourcefulness of these early Early and Middle Holocene societies

Keywords Organic materials, plant fibres, animal sinew, archaeobotany, biomolecular analysis

Introduction

Our understanding of the origins and development of technologies based on organic raw materials remains limited because of their rare preservation in the archaeological record, which is possible only under specific conditions like lack of humidity or in wet, oxygen-free environments. This preservation bias has significantly distorted our understanding of the role of these technologies in human evolution and social organisation. While a few archaeological sites have provided direct evidence for plant and animal-based crafts, these findings are often related to a narrow range of activities and/or products. This is the case with Palaeolithic wooden weaponry (e.g. Schoch et al. 2015; Leder et al. 2024) or digging sticks (Rios-Garaizar et al. 2018; Aranguren et al. 2018). Beyond the wooden remains that survive, the few exceptionally well-preserved Mesolithic sites, such as Starr Carr, North Yorkshire, United Kingdom (Milner et al. 2018) or Zamostje, Moscow Oblast, Russia (Lozovskaya/Lozovski 2016) and others[1], and Neo-

1 Gramsch 2000; Gramsch 2006; Lübke et al. 2011; Andersen 2013; Skaarup/Grøn 2004; Glykou 2016; Bailey et al. 2020.

lithic sites, such as La Draga, Catalonia, Spain (Piqué et al. 2015) or La Marmotta, Autonomous Province of Bolzano – South Tyrol, Italy (Caruso et al. 2021), show the wide range of plant-based artefacts and raw materials used, opening exceptional windows on the role of these technologies for past societies.

In the case of animal products used for crafts in prehistory – such as sinew, feathers (cf. Kirkinen in this volume), and leather – the evidence is even more limited. However, a few extraordinary cases have provided glimpses into their use. Sinew, for example, has been identified in association with Palaeolithic composite tools such as hafted stone points, where microscopic analysis of residues has revealed traces of collagen fibres used as binding material (Golovanova et al. 2024). Leather artefacts are similarly rare but have been recovered in waterlogged or arid environments where preservation conditions are favourable. For instance, leather shoes from the Chalcolithic period were discovered in the Areni-1 Cave, Vayots Dzor Province in Armenia, showcasing the sophisticated techniques used to process and stitch animal hides (Pinhasi et al. 2010). In addition, the discovery in the Alps of Ötzi, the Iceman, South Tyrol, Italy, has revealed the extensive use of leather and fur as well as plant material for clothing and equipment, shedding light on prehistoric craftsmanship (Egg/Spindler 1993; Junkmanns et al. 2019).

Interdisciplinary approaches to plant-based artefacts integrating archaeobotanical and biomolecular disciplines are essential to fill this gap. These rare findings underscore the importance of interdisciplinary approaches, such as protein residue analysis and experimental replication, to better understand the role of animal products in prehistoric technologies and their ecological significance. Archaeobotanical studies applied to the identification of plant raw materials used and plant transformation processes have a long history[2]. Other approaches, such as Gas Chromatography coupled with Mass Spectroscopy (GC-MS), have been developed recently; they allow the identification of glues, tars and other plant exudates and have demonstrated the antiquity of some of the processes for their production (Regert 2004; Wadley et al. 2015). More recently, proteomic approaches based on high resolution mass spectrometry have been utilised and rapidly developed for the identification of ancient proteins (Hendy 2021; McGrath et al. 2019).

However, such evidence is insufficient to capture the full complexity of the ecological and technological knowledge embedded in these practices. The lack of a broader data set limits our capacity to appreciate the sophistication and adaptability of ancient human societies in their use of organic resources, as well as the relationship between these technologies and their surrounding environments. In this paper, we present a summary of the results of the interdisciplinary research carried out on the organic artefacts from the site of Cueva de los Murciélagos (Albuñol, Spain). This site offers a unique opportunity to study technologies based on plant and animal raw materials, thanks to the extraordinary preservation of items made possible by the arid conditions of the cave. The exceptional state of these remains allows a detailed reconstruction of past technological practices and ecological knowledge, providing valuable insights into the use and processing of organic resources in prehistoric contexts.

Archaeological context and materials

The Cueva de los Murciéalgos site: description and research history

The Cueva de los Murciéalgos site is located in southeastern Iberia, near Albuñol Village, Granada Province (Spain), at 450 m AMSL (Fig. 1). It is a karstic cave with minimal speleothem development, several stratified prehistoric occupations, and further unstratified objects spanning prehistoric times into the 19th century. The latter materials correspond to the goods deposited in the cave during its use as a burial place in recent history. The importance of the site lies in the fact that it has yielded the oldest and best-preserved organic assemblage of materials in Europe dating from the Mesolithic to the Bronze Age, such as wooden objects and plant and animal fibre-based artefacts, on which this paper is focused (Martínez-Sevilla et al. 2023; Bertin et al. 2024).

The site was discovered in the 19th century and documented by M. de Góngora y Martínez (de Góngora 1868), but until the late 20th century only a few studies focusing on the plant fibre objects found at that time had been published (Alfaro 1984; Cacho et al. 1996). With the launch of the MUTERMUR (De los museos al territorio: Actualizando el estudio de la cueva de los Murciélagos de Albuñol(REF: CM/JIN/2021-009) project in 2021, the site was reassessed by radiocarbon dating and the materials were re-examined after having been stored for almost 150 years in two museums: Museo Arqueológico Nacional (MAN, Madrid) and Museo Arqueológico y Etnográfico de Granada (MAEG, Granada). Recent excavations conducted as part of the MUTERMUR project have brought to light additional extensive archaeological material – both organic and inorganic – that is currently under study.

The MUTERMUR interdisciplinary research project has used advanced archaeometry to gain deeper insights into the site. Techniques such as high-precision radiocarbon dating, Bayesian modelling, microscopic examination and proteomics of perishable materials have been systematically employed. These efforts have significantly improved the chronological framework of the site, revealing a 2000-year gap between the Mesolithic and Neolithic occupations (Martínez-Sevilla et al. 2023). Radiocarbon dating has so far identified three distinct phases of material deposition within the cave (Tab. 1). The earliest, associated with Mesolithic hunter-gatherer groups, dates from around 7500–7000 BC and is characterised by the production of simple

2 López i Bultó 2015; Schoch et al. 2015; Milks 2018; Vidal-Matutano et al. 2021; Vidal-Matutano et al. 2024; Herrero-Otal 2024; among others.

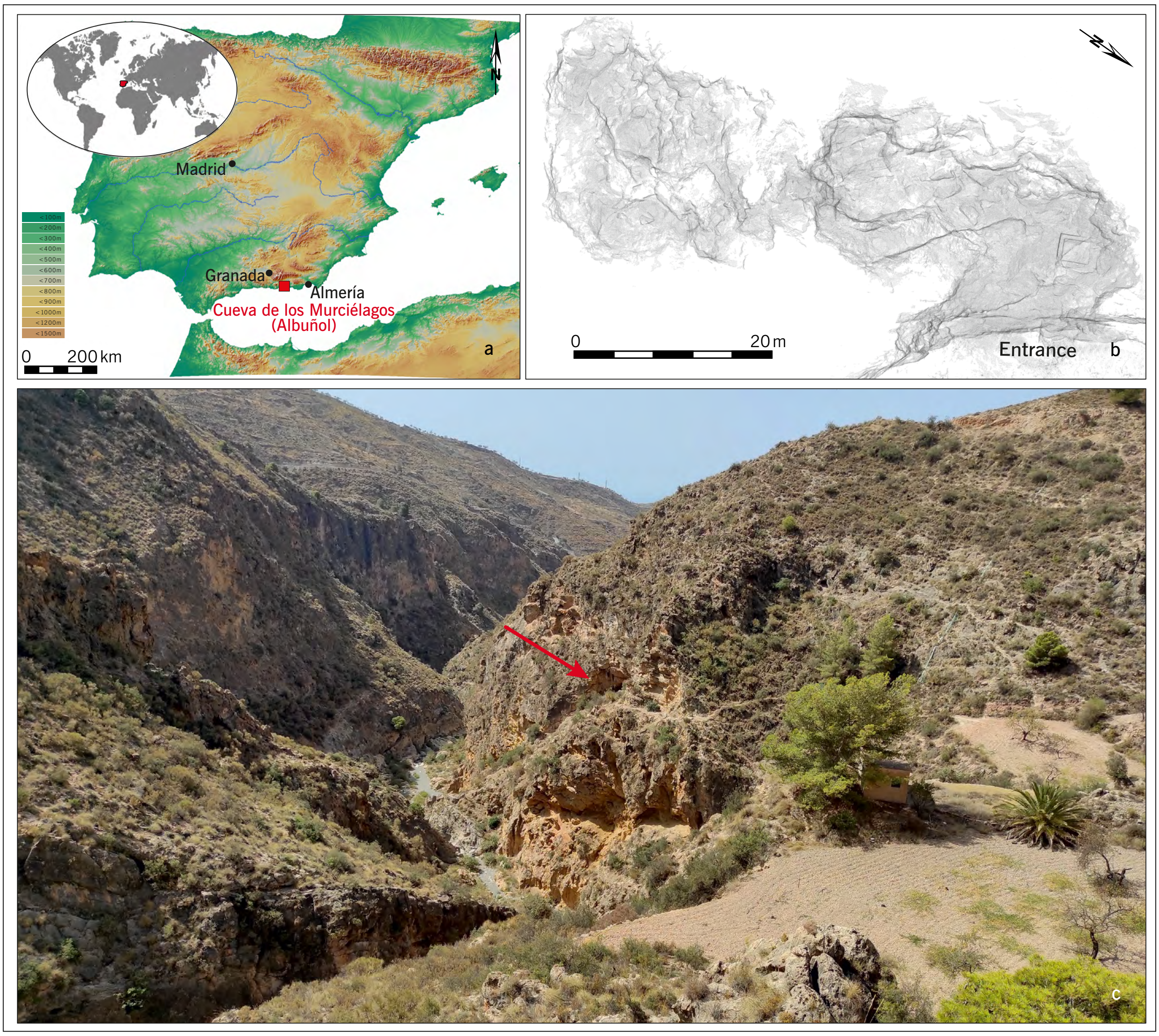

Fig. 1a–c The site of Cueva de los Murciélagos: a location of Cueva de los Murciélagos in southeast Spain (Albuñol, Granada, Spain); b plan of the cave made with the 3D model; c view from the north toward the Angosturas gorge and cave entrance (red arrow).

Abb. 1a–c *Der Fundplatz von Cueva de los Murciélagos: a Lage der Cueva de los Murciélagos im Südosten Spaniens (Albuñol, Granada, Spanien); b Plan der Höhle, erstellt aus einem 3D-Modell; c Blick von Norden auf die Angosturas-Schlucht und den Höhleneingang (roter Pfeil).*

twined baskets. The second phase, associated with Neolithic farming communities, dates around 5400–4200 BC. During this period, there was a notable diversification of artefact types, including the use of more diverse techniques involved in raw material processing and basketry (Martínez-Sevilla et al. 2023). Furthermore, a collection of archery artefacts, including sinew bowstrings (Bertin et al. 2024), is also associated with Neolithic groups. The third phase dates to the Bronze Age (1900–1700 BC) and is represented by a wooden shaft.

The perishable materials

The materials included in this paper are all currently deposited in the MAN and MAEG museums, apart from a twisted cord found during the recent archaeological campaigns developed within the MUTERMUR project.

Basketry elements: The basketry from the cave constitutes the most diverse and extensive assemblage of such items from southern Europe. Different production techniques are well represented, including twining (N = 10) (Fig. 2a–b), rhomboid twining (N = 6), pseudobraiding/*cofín* (N = 6; cf. Fig. 2c), braiding (N = 1; cf. Fig. 2d) and coiling (N = 11; cf. Fig. 2e–e,1). In addition, many of the objects are decorated, either by geometric motifs made of dyed fibres, some of which were studied in the 1990s (Cacho et al. 1996), or by the application of handles reinforced with pieces of animal skin. De Góngora (1868) reported in his publication that some of the baskets preserved diverse contents, such as *Papaver somniferum* capsules in one case and human hair in another. There are also other fibre-based objects of unknown function associated with the site, such as a set of four fibre-linked rings that form a kind of chain.

Fastening elements, cords and sandals: In addition, wooden and cane arrow shafts have been identified among

Artefact inventory ID	Radiocarbon Lab ID	Objects and technical description	Materials	Raw material taxonomical identification	Anatomical part	Radiocarbon date (BP)	Calibrated radiocarbon dates (BC)		Reference
							1σ	2σ	
CM-MAN581	Beta-627334	Simple twined basket	Plant fibres	*Stipa tenacissima*	Leaf	8300 ± 30	7504–7370	7531–7353	Martínez-Sevilla et al. 2023
CM-MAN626	Beta-628426	Linked rings	Plant fibres	*Stipa tenacissima*	Leaf	8400 ± 30	7481–7361	7501–7346	Martínez-Sevilla et al. 2023
CM-MAN579	Beta-627332	Simple twined basket	Plant fibres	*Stipa tenacissima*	Leaf	8350 ± 30	7469–7361	7487–7332	Martínez-Sevilla et al. 2023
CM-MAN580	Beta-627333	Simple twined basket	Plant fibres	*Stipa tenacissima*	Leaf	8320 ± 30	7464–7356	7486–7317	Martínez-Sevilla et al. 2023
CM-P287	Beta-684048	Twisted cord	Animal sinew	*Sus* sp., *Capreolus capreolus*	Sinew	6220 ± 30	5215–2070	5290–5045	Bertin et al. 2024
CM-MAN1139/532	Beta-692876	Arrow shaft, Fastening fibres	Plant cane, Animal sinew	*Phragmites australis*, Non-identified	Stem, Sinew	6220 ± 30	5215–2070	5290–5045	Bertin et al. 2024
CM-MAN617	Beta-627342	Diagonal twined basket	Plant fibres	*Stipa tenacissima*	Leaf	6210 ± 30	5156–5067	5281–5041	Martínez-Sevilla et al. 2023
CM-MAN594	Beta-628427	Pseudo-braided/*cofín* basket	Plant fibres	*Stipa tenacissima*	Leaf	6150 ± 30	5187–5013	5206–5001	Martínez-Sevilla et al. 2023
CM-MAN1138/532	Ua-78245	Arrow shaft, Arrowhead, Fastening fibres	Plant cane, Wood, Animal sinew	*Phragmites australis*, *Salix* sp., Non-identified	Stem, Twig, Sinew	6124 ± 30	5205–5025	5215–4990	Bertin et al. 2024
CM-MAN591b	Beta-692877	Twisted cord	Animal sinew	*Capra* sp.	Sinew	6100 ± 30	5055–4950	5210–4905	Bertin et al. 2024
CM-MAN598	CSIC-1133	Central core sandal	Plant fibres	*Stipa tenacissima*	Leaf	6086 ± 45	5056–4910	5206–4846	Cacho et al. 1996
CM-MAN609	CSIC-1134	Central core sandal	Plant fibres	*Stipa tenacissima*	Leaf	5900 ± 38	4826–4720	4886–4691	Cacho et al. 1996
CM-MAN616	CSIC-1132	Coiled basket	Plant fibres	*Stipa tenacissima*	Leaf	5861 ± 48	4795–4680	4844–4556	Cacho et al. 1996
CM-MAN611	Beta-627331	Simple twined basket	Plant fibres	*Stipa tenacissima*	Leaf	5640 ± 30	4533–4406	4542–4367	Martínez-Sevilla et al. 2023
CM-MAN603	Beta-627330	Central core sandal	Plant fibres	*Stipa tenacissima*	Leaf	5630 ± 30	4499–4371	4537–4366	Martínez-Sevilla et al. 2023
CM-MAN615	Beta-627341	Coiled basket	Plant fibres	*Stipa tenacissima*	Leaf	5580 ± 30	4446–4365	4484–4350	Martínez-Sevilla et al. 2023
CM-MAN623	Beta-627337	Pseudo-braided/*cofín* basket	Plant fibres	*Stipa tenacissima*	Leaf	5570 ± 30	4443–4361	4454–4348	Martínez-Sevilla et al. 2023
CM-MAN624	Beta-627336	Pseudo-braided/*cofín* basket	Plant fibres	*Stipa tenacissima*	Leaf	5550 ± 30	4443–4351	4447–4346	Martínez-Sevilla et al. 2023
CM-MAN625	Beta-627335	Braided basket	Plant fibres	*Stipa tenacissima*	Leaf	5550 ± 30	4443–4351	4447–4346	Martínez-Sevilla et al. 2023
-	CSIC-246	-	Plant fibres	-	-	5400 ± 80	4438–4262	4453–4173	López 1978

Tab. 1 Technical, raw material identification and unmodelled and modelled radiocarbon dates for the materials from the Cueva de los Murciélagos site included in the current paper.

Tab. 1 *Technische Daten, Identifizierung des Rohmaterials und nicht modellierte sowie modellierte Radiokarbondaten für die Materialien aus der Fundstätte Cueva de los Murciélagos, die in der vorliegenden Arbeit berücksichtigt wurden.*

Fig. 2a–e Examples of Mesolithic and Early Neolithic baskets from Cueva de los Murciélagos: a Basket CM-MAN579 (7487–7332 cal BC, Beta-627332); b basket CM-MAN581 (7531–7353 cal BC, Beta-627334); c basket CM-MAN594 (5206–5001 cal BC, Beta-628427); d basket CM-MAN625 (4447–4346 cal BC, Beta-627335); e.e,1 basket fragment CM-MAN615 (4484–4350 cal BC, Beta-627341).

***Abb. 2a–e** Beispiele für mesolithische und frühneolithische Körbe aus der Cueva de los Murciélagos: a Korb CM-MAN579 (7487–7332 cal BC, Beta-627332); b Korb CM-MAN581 (7531–7353 cal BC, Beta-627334); c Korb CM-MAN594 (5206–5001 cal BC, Beta-628427); d Korb CM-MAN625 (4447–4346 cal BC, Beta-627335); e.e,1 [MH1] Korbfragment CM-MAN615 (4484–4350 cal BC, Beta-627341).*

the organic material assemblage in the two museums, and additional finds have been made during the recent excavations. The ends of some shafts are tightly wrapped with fibres – binding feathers to the shaft in some instances (Fig. 3a–a,1) – or fastening wood and cane together in cases where the shaft combines both materials. The cord assem-

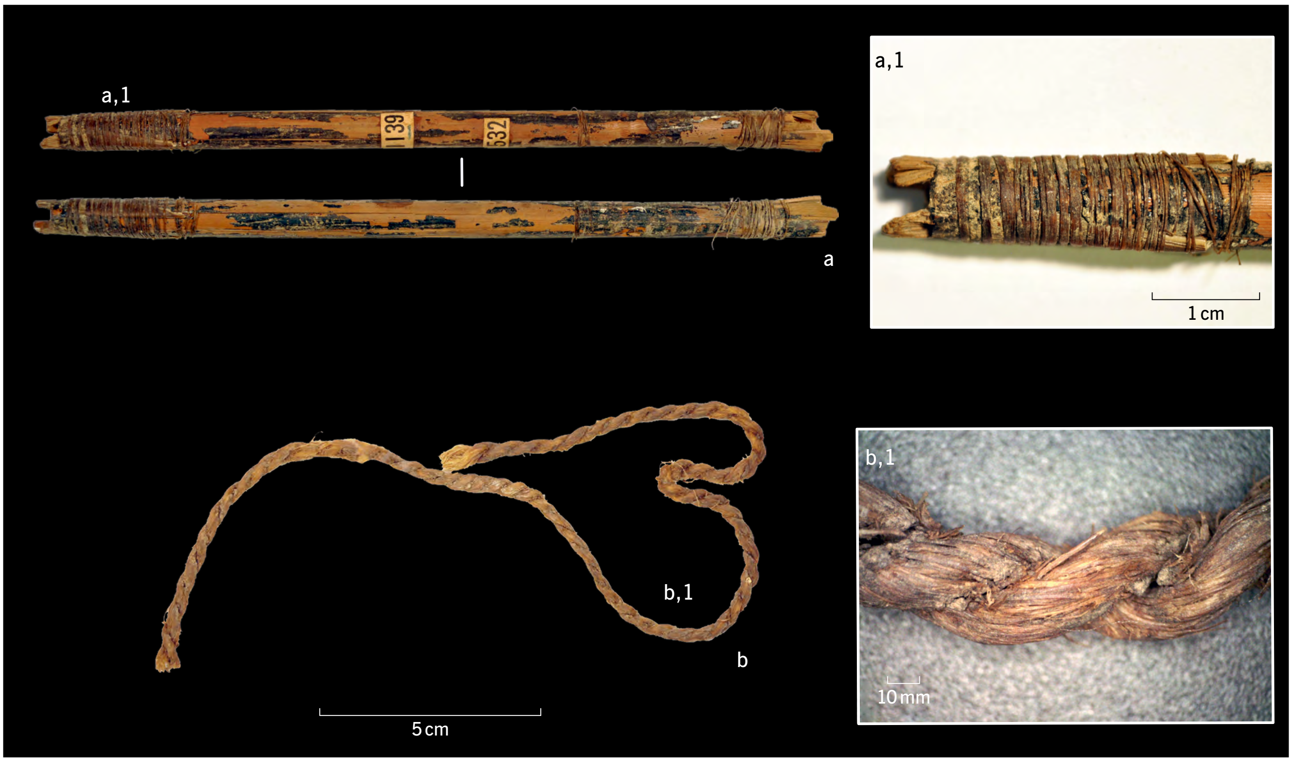

Fig. 3a–b Early Neolithic archery elements from Cueva de los Murciélagos: a.a,1 Cane arrow shaft CM-MAN1139/532 (5290–5045 cal BC, Beta-692876); b.b,1 Cord fragment CM-MAN591b (5210–4905 cal BC, Beta-692877).

Abb. 3a–b *Frühneolithische Bogenschießelemente aus Cueva de los Murciélagos: a.a1 [MH2] [MH3] Pfeilschaft aus Schilfrohr [CM4] CM-MAN1139/532 (5290–5045 cal BC, Beta-692876); b.b,1 [MH5] Schnurfragment, identifiziert als mögliche Bogensehne CM-MAN591b (5210–4905 cal BC, Beta-692877).*

blage consists of ten examples; two are twisted cords, one of which is shown in Fig. 3b–b,1 (CM-MAN591b and CM-P287). Some of their characteristics are quite similar; for example, both are two-ply twisted cords (Szz) with closed twist angles (53/55°–60°) and two twists per centimetre. One cord measures 34 cm, the other 59 cm in length. The remaining eight cords are braided (three-ply) and vary in length and width. Some of the cords resemble fastening elements found on sandals recovered at the site. Sandals are an important part of the inventory (Alfaro 1984) distinguished two types of sandals: simple (N = 2; Fig. 4a) and central core (N = 20; Fig. 4b–d), differentiated by the way the sole was made. Notably, the number of sandals available is increasing, as new examples have been recovered in recent archaeological fieldwork. The simple type has no preserved fasteners, while the central core type has a small group of fibres extending from the base of the sole, which may be placed between the first and second toes. These fibres are also connected to a braid attached to the centre of the sandal, which could be tied around the ankle. The footwear shows clear signs of wear on the lower part of the sole.

Methodology

Raw materials identification by optical and electronic microscopy

The objects included in this study were recorded in the museums and the laboratory and documented by an extensive photographic record (Nikon D5000 camera with a NIKKOR AF-S DX 18-55 mm VR lens). In addition, detailed images were taken with a portable Dino-Lite Edge digital microscope AM7915MZT (× 20 to × 220).

The materials were sampled using tweezers and a blade, both of which were cleaned with 96 % ethanol between samples to prevent cross-contamination. Although sampling is an inherently destructive process, small fibre fragments, just a few millimetres in size, are required for identification purposes. Due to the fragility of these objects, small pieces often break off during restoration or storage, and in most cases, these fragments were used for sampling to minimise further damage to the objects.

The collected samples were used for microscopic analysis. For optical microscopic (OM) studies, observations were made using an Olympus BX51 transmitted-light bright-dark field microscope (× 50 to × 500), equipped with an Olympus DP26 camera and linked to Olympus cellSens software for imaging and documentation. The OM observations were developed in the Archaeobotany Laboratory of the Prehistory Department at the Universitat Autònoma de Barcelona (UAB). To obtain high-quality images and verify identifications, selected samples were examined using a Zeiss Merlin field emission scanning electron microscope (SEM) at the Servei de Microscòpia i Difracció de Raigs X (UAB). Depending on the availability of the sample, some samples were coated with a 15 nm gold layer using an Emitech K550 sputter coater.

Fibre identification was carried out through a comparative analysis of the microhistological characteristics of the

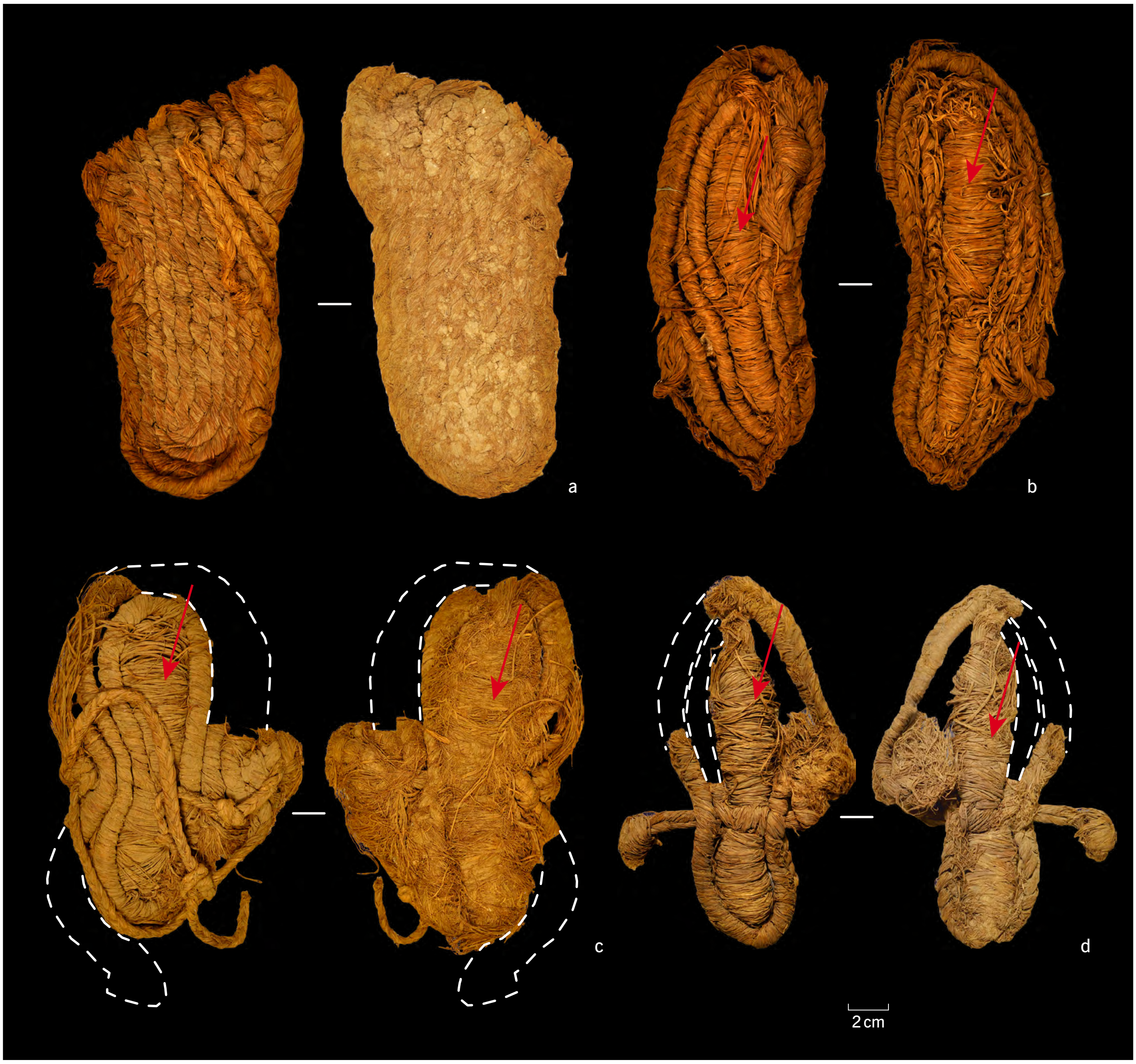

Fig. 4a–d Middle Neolithic sandals from Cueva de los Murciélagos: a Sandal CM-MAN603 (4537–4366 cal BC, Beta-627330); b sandal CM-MAN611 (4542–4367 cal BC, Beta-627331); c sandal CM-MAN598 (5206–4846 cal BC, CSIC-1133); d sandal CM-MAN609 (4886–4691 cal BC, CSIC-1134).

***Abb. 4a–d** Mittelneolithische Sandalen aus der Cueva de los Murciélagos: a Sandale CM-MAN603 (4537–4366 cal BC, Beta-627330); b Sandale CM-MAN611 (4542–4367 cal BC, Beta-627331); c Sandale CM-MAN598 (5206–4846 cal BC, CSIC-1133); d Sandale CM-MAN609 (4886–4691 cal BC, CSIC-1134).*

archaeological samples and modern reference materials. In the case of plant fibres, the archaeological samples were compared with a reference collection of plants traditionally used for fibre production and found naturally in the vicinity of the site. These included species such as *Stipa tenacissima*, *Stipa gigantea* and *Lygeum spartum*. For sinew samples, the archaeological specimens were compared with modern sinew of horse *(Equus* sp.*)*, deer *(Cervus* sp.*)* and water buffalo *(Bubalus bubalis)*, as traditionally used in modern archery. The modern plant and animal materials used for comparison were prepared using standard techniques. For plant fibres, this involved collecting, drying, moistening and physically processing the plants, while sinew samples were cleaned, dried and stretched. These preparations ensured that the modern materials were suitable for accurate comparative analysis.

Elemental, spectroscopic and proteomic analysis

Elemental Analysis: Elemental analysis was carried out using an EDS Oxford LINCA-X-Max detector (Servei de Microscòpia i Difracció de Raigs X, UAB) at a resolution of 15 kV; to preserve the archaeological samples for possible re-use, they were not coated with carbon. These analyses were carried out on two archaeological samples (twisted cords) and on reference samples of modern animal sinews.

Spectroscopic Analysis: The same samples were analysed by Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy using a Perkin Elmer Frontier instrument (Cultures – Environnements. Préhistoire, Antiquité, Moyen Âge [Le CEPAM], Université Côte d'Azur). This non-destructive technique allows the identification of the molecular and compositional properties of the

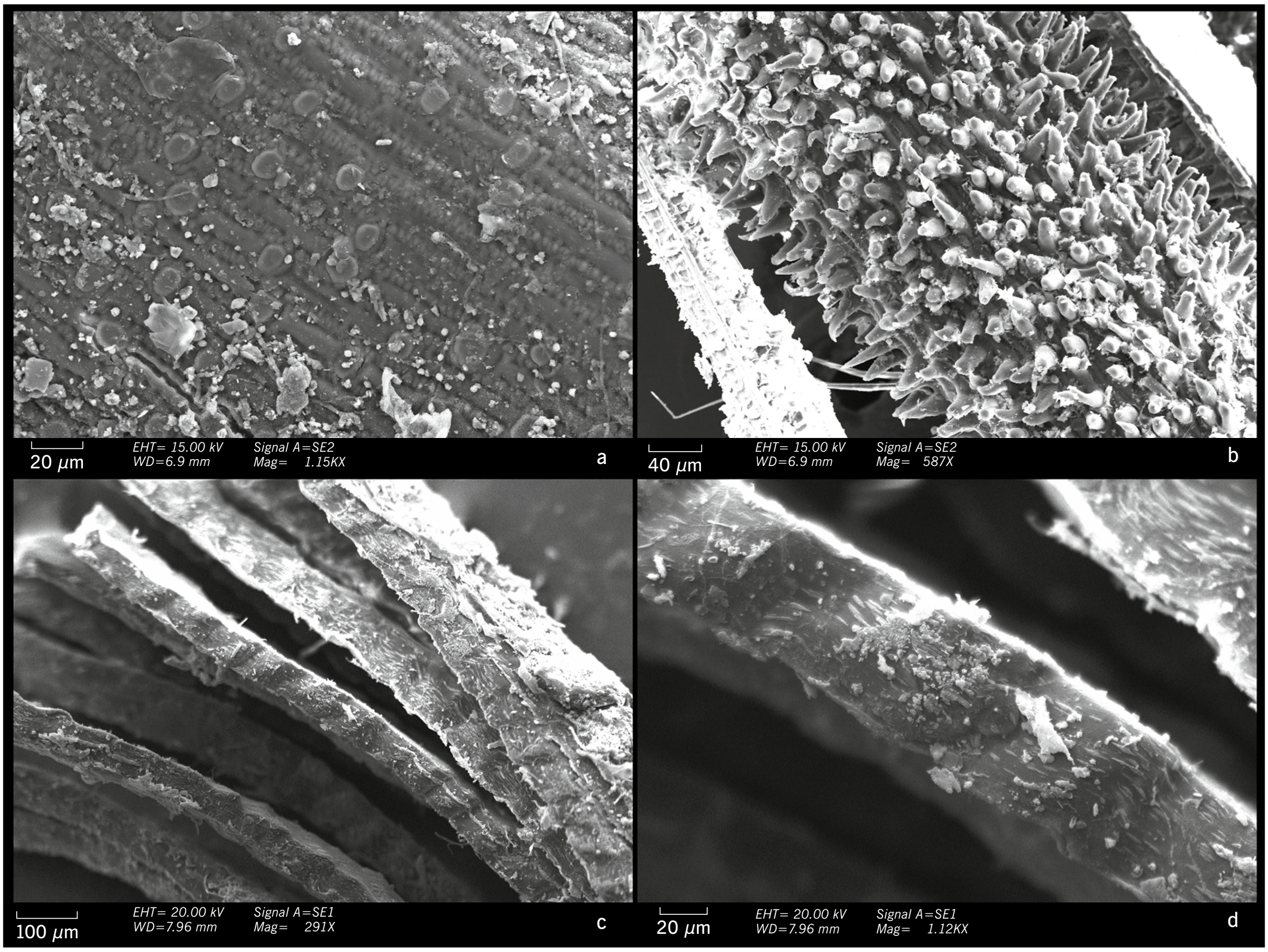

Fig. 5a–d Fibre-based objects from Cueva de los Murciélagos SEM images: a Adaxial epidermis of archaeological *Stipa tenacissima* (CM-MAN583); b abaxial epidermis of archaeological *Stipa tenacissima* (CM-MAN583); c–d sinew archaeological sample (CM-MAN591b).

***Abb. 5a–d** Faserbasierte Objekte aus der Cueva de los Murciélagos SEM-Bilder: a Adaxiale Epidermis der archäologischen Stipa tenacissima (CM-MAN583); b Abaxiale Epidermis der archäologischen Stipa tenacissima (CM-MAN583); c–d Archäologische Sehnenprobe (CM-MAN591b).*

samples. The spectral data were processed using Spectragryph v1.2.16.1 software and compared with published databases and references (Jung 2000; Monnier et al. 2018).

Proteomic Analysis: Based on the findings that the cords were of animal origin, Zooarchaeology by Mass Spectrometry (ZooMS) was used to determine their taxonomic source by analysing the collagen in the samples. Analysis was carried out using a Bruker ultrafleXtreme MALDI-ToF-MS at the CoEMS facility at the University of York. The spectral data were averaged and processed using mMass software (Strohalm et al. 2008) and then compared against established databases of collagen peptide markers (Buckley et al. 2009; Kirby et al. 2013; Welker et al. 2016).

Results

A thorough analysis of the samples of fibre-based objects and fastening elements from the arrow shafts revealed that all the baskets, braided cords, and footwear were based on plants, while the twisted cords and fasteners on the shafts were of animal origin.

With regard to plant fibre-based materials (baskets, braided cords and footwear), all samples confirmed the use of esparto grass *(Stipa tenacissima)*. Microscopic examination revealed distinct microanatomical features characteristic of modern esparto grass (Fig. 5a–b) that were not observed in other *Poaceae* plants with esparto-like properties, such as *Stipa gigantea* and *Lygeum spartum*.

In certain objects, variations in the treatment of fibres were visible to the naked eye. Physical treatments such as crushing can be easily identified by direct observation or histological analysis, whereas processes such as retting and fermentation are not visible. Fibre treatments varied according to the craft techniques used throughout the assemblage. Both raw and crushed esparto were used in basketry. Raw esparto was mainly used for objects made using twining and braiding. Pseudobraiding was also made primarily from raw esparto, with one exception. Coiling baskets used both types of processed esparto: raw esparto formed the bundles, while the stitches showed signs of opened fibres, indicating that the leaves had been crushed. The braided cords were made with crushed fibres, as were both types of sandals. In addition, the selection of leaves according to size was evident. The smaller diameter of the esparto leaves used in Mesolithic objects compared to those from the Neolithic suggests that younger leaves were selected for manufacturing Mesolithic artefacts than those made in the Neolithic period.

In contrast, observations made under an OM on two twisted cords and the fastening elements from the arrow shaft samples revealed no plant characteristics, suggesting an animal origin. These materials were then examined using an SEM. This high magnification examination of the two twisted cord samples revealed parallel fibres running along their length, with a hierarchical structure with wavy fibres (cf. Figure 5c–d) very similar to that of collagen-rich animal tissue. While the results for the cords were good, as the characteristics of the raw material were clearly visible, this was not the case for the shaft fasteners, as the presence of an unidentified substance (perhaps an adhesive like birch tar) made observation more difficult.

Nevertheless, elemental analysis confirmed an animal origin. FTIR spectroscopy performed on both the tendons and the ligaments revealed that the material was composed of collagen, the main component of connective tissue. Further comparison with modern sinew confirmed the identification as sinew. ZooMS was carried out on small samples from each cord to identify the animal from which it came. The analysis showed that sample CM-MAN-591b was from *Capra* sp. (goat), while sample CM-P287 was composed of several species, including *Sus* sp. (pig) and *Capreolus capreolus* (roe deer).

Discussion

Material diversity and functional specialisation

Prehistoric communities in the Cueva de los Murciélagos site employed a variety of material selection and processing strategies. The predominant use of *Stipa tenacissima* for the production of baskets, sandals, and other fibre-based goods has been documented (Martínez-Sevilla et al. 2023), demonstrating a systematic approach to the processing of esparto, depending on the type of objects that should be produced, the technique used to fashion them, and their function. In addition, I. Bertin et al. (2024) highlight the choice of materials for the construction of archery equipment, identifying the use of animal sinew -goat, pig and roe deer- for bowstrings, as well as willow *(Salix* sp.*)*, olive wood *(Olea europaea)*, maple *(Acer* sp.*)*, and a variety of reed *(Phragmites* sp.*)* for arrow shafts.

The selection of these materials reflects an advanced understanding of their mechanical properties. Both studies underline a deep understanding of the structural properties of raw materials and their suitability for meeting specific functional requirements.

Technological continuity and crafts

From a technological and functional point of view, the results of our studies underline a technological continuity across different craft domains. On the one hand, a long-term transmission of fibre-based craft knowledge is observed, as crafts such as basketry have been transmitted and refined over millennia. On the other, the results demonstrate a dynamic process of innovation within these prehistoric communities. By integrating new techniques, Neolithic populations in southern Iberia demonstrated remarkable adaptability in material use, both plant and animal, and in technological development.

Environmental adaptation and resource management

The systematic analysis of the fibres used as raw material at the Cueva de los Murciélagos site confirmed the use of *Stipa tenacissima* for craft purposes (Martínez-Sevilla et al. 2023). The use of this species was suggested by previous studies through macroscopical observation (Alfaro 1984). In the current study, microscopic examination revealed microanatomical characteristics visible in modern esparto samples that are absent in other plants of the *Poaceae* family with esparto-like properties. Although palynological studies (Revelles 2023) suggest that other hydrophytic plants should have been present relatively close to the cave, no other plants were found in the analysis of fibre-based products from the site, suggesting that the Mesolithic and Neolithic human groups that occupied or used the cave relied on the natural resources available locally.

Esparto grass is still used today in traditional crafts, and its use goes back to prehistory, as shown by the materials studied here. However, these are not the oldest remains found in Iberia. The oldest direct evidence of the use of esparto grass discovered to date was found at Coves de Santa Maira, Alacant Province, Spain (9600 ± 40–7370 ± 40 cal BC), where three charred fragments of braided cord and an untwisted fibre of this material were documented (Aura-Tortosa et al. 2019). However, some other archaeological examples have provided evidence of its use, largely thanks to the arid preservation conditions that prevail across much of the peninsula. On the east coast, fragments of a woven basket made of esparto grass have been found at Cova de les Cendres, Alacant Province, Spain (4510 ± 40 cal BC; Bernabeu/Fumanal 2009). However, the majority of finds are from southern Iberia and date to more recent periods: remains of a plaited cord at Villa Filomena, Valencian Community, Spain (3000–1800 cal BC), fragments of cords and plaited baskets at Cabezo Redondo, Alacant Province, Spain (2429–2065 cal BC), braided cords and plaited, twisted and coiled baskets at Ifré, Almería Province, Spain (2360–1910 cal BC; Alfaro 1984), a braided cord and remains of woven baskets at Las Angosturas de Gor, Province of Granada, Spain (2350–1919 cal BC; Cacho et al. 1996), and a corded net documented at Castellón Alto, Province of Granada, Spain (1900–1600 cal BC; Molina et al. 2003).

Different hypotheses for the use of birch bark tar in the production of arrow shafts can be proposed, including adhesive, decorative and structural consolidation purposes. These hypotheses are supported by archaeological evidence (Desmond Clark et al. 1974) and ethnoarchaeological studies (Šmit 2016) that document the use of adhesives and paintings on arrows, or birch bark tar used similarly on other wooden artefacts (Kabaciński et al. 2023; Koch et al. 2024).

The efficient use of locally available materials reflects not only a deep understanding of the local ecosystem but also an ability to adapt technological practices to specific environmental conditions. This has also been suggested in other contemporary sites in the northeastern part of the Iberian Peninsula, such as La Draga, where an extensive collection of wooden (López i Bultó 2015; Piqué et al. 2021) and plant fibre-based objects has been recorded[3], indicating a sophisticated technological and environmental knowledge of Neolithic communities in the management and use of plant resources.

Conclusions

The natural drying conditions of the Cueva de los Murciélagos site played a crucial role in the preservation of organic materials, providing a rare and valuable window into the daily life and technological innovations of its prehistoric inhabitants. The multidisciplinary research developed under the MUTERMUR project highlights the complexity of prehistoric technological systems. The integration of plant and animal-based materials, together with advanced manufacturing techniques, demonstrates the remarkable technological expertise of human communities dating back at least to the Mesolithic when subsistence patterns were based on hunting and gathering. These technological skills expanded over time, particularly in the use of plant fibres and animal sinew, which were probably applied to activities related to both hunting and agriculture as early farming practices emerged in southern Iberia (Martínez-Sevilla et al. 2023; Bertin et al. 2024).

Future research involving experimental archaeology and further biomolecular analysis could improve our understanding of the specific functional properties of these materials and their wider implications for Neolithic social organisation, technological progress and the transmission of cultural knowledge.

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Source of figures

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1 F. Martínez-Sevilla, Alcála de Henares; a Wikipedia/Natural Earth Data; b MUTERMUR; c F. Martínez-Sevilla, Alcalá de Henares
2 M. Herrero-Otal, Bellaterra; F. Martínez-Sevilla, Alcalá de Henares
3 I. Bertin, Bellaterra; F. Martínez-Sevilla, Alcalá de Henares
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