University of Helsinki
Dissertationes Universitatis Helsingiensis
79/2024

Plant fibre identification methods in research of heritage linen textiles

Jenni A. Suomela

ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Education of the University of Helsinki, for public examination in lecture hall 107, University Athena building, Siltavuorenpenger 3 A,
on 19 April 2024, at 12 o'clock noon.

Helsinki 2024

Supervisors

Professor Riikka Räisänen
Department of Education
University of Helsinki, Finland

Postdoctoral researcher Krista Wright
Department of Education
University of Helsinki, Finland

Preliminary examiners

Head of the Applied Research Department Christina Margariti
Hellenic Ministry of Culture, Greece

Associate Professor Camilla Growth
Craft University of South-Eastern Norway, Norway

Opponent

Senior Lecturer Susanna Harris
University of Glasgow, Scotland

Custos

Professor Riikka Räisänen
Department of Education
University of Helsinki, Finland

The Faculty of Education uses the Ouriginal system (plagiarism recognition) to examine all doctoral dissertations.

Cover image: Jenni A. Suomela

Publisher: University of Helsinki
Series: Dissertationes Universitatis Helsingiensis 79/2024

ISBN 978-951-51-9723-8 (print)
ISBN 978-951-51-9722-1 (online)
ISSN 2954-2898 (print)
ISSN 2954-2952 (online)

PunaMusta, Joensuu 2024

Abstract

The doctoral thesis falls within the discipline of craft science, with the aim being to discover a means to identify plant fibres in heritage textiles. I have above all developed microscopy methods to separately identify flax (*Linum usitatissimum L.*), hemp (*Cannabis sativa*) and stinging nettle (*Urtica dioica*) fibres. The research material has also revealed the significant role played by cotton (*Gossypium spp.*) in linen textiles. This is the first research project to identify commercially cultivated cotton at the species level based on its fibre morphological properties. The existing literature often refers to textiles made of plant fibres using the general term linen because the material has been unidentifiable after production. My thesis offers tools for conducting detailed research on this type of textile.

In the theoretical framework of the study, I have tied the knowledge gained from fibre identification to research models utilised in the deep analysis of objects. I have introduced natural scientific application methods through a focus on heritage science – a field of research not so well known in Finland yet.

My research material consists of plant fibre textiles from different time periods in Finland, from surrounding areas and from the Khanty and Mansi peoples, also part of the Finno-Ugrian language family. The oldest material is from the Late Iron Age (12th century CE), namely fibre finds from the archaeological excavations of Ravattula, Ristimäki. The largest body of material derives from the textiles collected by the photographer I. K. Inha in White Karelia in the year 1894, but I have additionally utilised photographs and written resources. The cotton materials, dating as far back as the 14th century in Finland, represent recent archaeological and heritage finds.

With respect to the fibre studies, the unique contribution of my research has been the development of new methods. I compiled a three-stage procedure that makes it possible to differentiate flax, hemp and nettle from each other by comparing their morphological differences. The procedure was tested throughout the thesis project with fibres of different ages and conditions – it was even possible to identify textiles from different archaeological periods with it. I have devoted considerable effort to developing suitable cross-cutting methods for heritage textile fibres. In addition to light microscopy, X-ray spectroscopy and tomography methods have been used to identify and study heritage materials. While they did not aid in identifying the fibres, I was able to identify alternative and suitable applications in heritage textile research. With cotton, I was able to identify species-specific properties at the fibre level. Building on previous studies in the existing literature, I have been able to shed light on the obscure use of the term linen and offer recommendations for its proper use. I have made the objects 'talk' and 'tell' about the history of plant fibre textiles; the archaeological samples especially have revealed much about the spread of different textile materials in Finland. I have, in a material-driven manner, provided new information on the textile tradition in White Karelia, shed light on the early history of cotton in Finland and, with justified methods, identified bast fibres from Late Iron Age textiles.

My research has considerable value for research on heritage plant fibre textiles precisely because species-specific identification makes it possible to do much more profound research on the cultural history of these types of textiles. Through material identification, it is possible focus on much larger issues, such as the development of trade connections and agriculture, as well as various cultural currents – which makes advancements in fibre identification important and valuable.

Keywords: linen, heritage textiles, microscopy, fibre identification, flax, nettle, hemp, cotton

Acknowledgements

What an amazing journey writing this dissertation has been! I enjoyed every moment of it. Even though I was able to answer some questions, or at least advance the research around them, even more questions have emerged. Many smaller research projects have happened alongside this dissertation and so many are waiting. My future is not going to be boring!

Firstly, I want to thank my supervisors Professor Riikka Räisänen and PhD Krista Wright for supporting me whenever I needed. I am also grateful for the trust I received and freedom to conduct research in my own terms. Special thanks to Riikka for letting me teach at the Craft teacher education during the process. Although I never planned to be a teacher, I have understood, that through teaching I can contribute to making the world a better place. And Krista, without you there would not be this dissertation. Huge thanks for introducing me to textile archaeology, heritage science methods and most of all, fibres!

I have not done this on my own, I want to show my gratitude to my co-authors PhD Mira Viljanen, PhD Kirsi Svedström and PhD Heikki Suhonen from the Physics Department of the University of Helsinki. You have all been so brave and open-minded about our co-operation and this has hopefully been just a steppingstone for our future collaboration. PhD Sanna Lipkin, you have been so much more than a co-author during all these years, thank you.

Special thanks to my mental mentors, PhD Ildikó Lehtinen and MA (education) Tupu Mentu. Thank you for guiding me towards my current position and introducing me the beauty of textiles. I owe my deepest gratitude to the Nanomicroscopy Centre of Aalto University and especially to Professor Janne Ruokolainen and PhD Jani Seitsonen, who have so warmly welcomed me to NMC and use their facilities. Also, the Geology Department of University of Helsinki in Kumpula has provided their facilities of polarised light microscopes to advance my research. Ville Heiskanen from Helsinki University's Botanical Gardens in Kumpula, Pertti Pehkonen and Merja Pulkkinen from Kaisaniemi Botanical Gardens, conservators in The Finnish Heritage Agency's Collections and Conservation Centre, intendent of the Finno-Ugric Collection Anna-Mari Immonen in The National Museum of Finland, have all had their role in within the process.

Sincere thanks for all the following foundations providing individual grants that enabled my doctoral research: The Cultural Foundation of Finland; Karjalaisen

Kulttuurin Edistämissäätiö; Helsinki University Funds, Kanslianeuvos Kaarlo Koskimiehen ja Irma Koskimiehen stipendirahasto; as well as all the numerous travel grant providers that permitted my participation to all those interesting conferences around the world.

It is so heart-warming to have such inspiring colleagues in the field who have provided me with possibility to grow as a researcher together with them. My deepest commendations to textile historian Git Skoglund from Sweden, PhD Satu Koivisto from the University of Turku, PhD Tuija Kirkinen from the University of Helsinki, PhD Riina Rammo from the University of Tartu, PhD Alex Snellman, and Professor Sirpa Kokko from the University of Eastern Finland.

Thanks for all my friends for keeping me together all these years. Very special thanks to my partner in crime with nettle, doctoral researcher Samica Sadik – you are my soul animal. Thank you for my family, especially my mum for believing in me for all these years. And then my anchors and sunshines, beloved Pinja and Osama — I cannot imagine what all you have had to bear. Thank you for standing my irregular working hours, waking up late and rarely having a proper holiday. Still, the food stayed on the table. Yet, I can say I am proud of myself that I had the guts, with the help of all the others mentioned above, to be able to pursue my dreams and as now, present this dissertation.

Helsinki, 20th of March 2024
Jenni A. Suomela

List of images and tables

List of images:

List of tables:

List of abbreviations

ATR	Attenuated total reflection
CHS	Cultural Heritage Science
FTIR	Fourier-transform infrared spectroscopy
Micro-CT	Micro computed tomography
Nano-CT	Nano computed tomography
PLM	Polarised light microscopy
RI	Reflective index
SEM	Scanning electron microscopy
SHG	Second harmonic generation
TEM	Transmitted electron microscopy
TLM	Transmitted light microscopy
WAXS	Wide-angle X-ray scattering

Index

List of original publications

This thesis is based on the following publications:

I Suomela, J. A., Vajanto, K., & Räisänen, R. (2018). Seeking nettle textiles–utilizing a combination of microscopic methods for fibre identification. *Studies in Conservation*, 63(7), 412-422.

II Suomela, J. A., Vajanto, K., & Räisänen, R. (2020). Examining the White Karelian textile tradition of the late nineteenth century—Focus on plant fibers. *Textile*, 18(3), 298-324.

III Suomela, J. A., Viljanen, M., Svedström, K., Wright, K., & Lipkin, S. (2023). Research methods for heritage cotton fibres: case studies from archaeological and historical finds in a Finnish context. *Heritage Science*, 11(1), 175.

IV Suomela, J. A., Suhonen, H., Räisänen, R., & Wright, K. (2022). Identifying Late Iron Age textile plant fibre materials with microscopy and X-ray methods—a study on finds from Ravattula Ristimäki (Kaarina, Finland). *Archaeological and Anthropological Sciences*, 14(3), 40.

V Suomela, J. (2023). My experiments with cross-sectioning textile fibres. In *Interdisciplinary Approaches to Research of North and Central European Archaeological Textiles: The Proceedings of the North European Symposium for Archeological Textiles (23rd–26th August 2021 in Oulu)* (pp. 289-298). Archaeological Society of Finland.

The publications are referred to in the text by their roman numerals.

The author's contribution to the publications

I JAS designed the study and collected and analysed the samples and textiles. JAS wrote the paper with contributions from KV and RR. The revision of the final draft was done by all writers.

II JAS designed the study and collected and analysed the samples and textiles. JAS wrote the paper with contributions from KV and RR. The revision of the final draft was done by all writers.

III JAS conducted and wrote the literary review in the introduction and the optical microscopy analysis and interpretation, interpreted the FTIR and SEM material and wrote the discussion and conclusion sections. MV and KS are responsible for all the WAXS measurements, the analysis and the text. KW did the SEM imaging and took the FTIR measurements. SL contributed the micro-CT sections.

IV JAS designed the study and did the microscopical analysis. HS did the micro-CT imaging and JAS interpreted the results. JS wrote the paper with contributions from HS, RR and KW. The revision of the draft was done by JAS, RR and KW.

V JAS wrote the paper independently.

1 Introduction

The doctoral thesis focuses on how object-based textile research can benefit from sophisticated fibre identification methods. Research on heritage textiles can greatly benefit from the micro-level knowledge that can be achieved via microscopy methods. Studying linen textiles through their material identifications contribute to a better understanding of cultural history, trade connections and agricultural development. Microscopy research can provide new perspectives on the craft skills, equipment, structures and techniques used at various time periods in history. In addition to providing indirect answers, microlevel research of textile material can also yield plenty of direct information. It is even now possible to identify the plant species used in the material. Processing and dyeing methods are also revealed under the microscope. Wear traces in the fibres show how the textile was handled. Additionally, degradation processes due to microbial activity or environmental conditions are detectable when closely examining the textiles.

My research focuses on the challenging nature of identifying the origin of the plant fibres used in textiles. I have concentrated on flax (*Linum usitatissimum L.*), hemp (*Cannabis sativa*) and stinging nettle (*Urtica dioica*) because they are the bast fibre plants traditionally utilised in Fenno-Scandinavia. In addition to these bast fibres, cotton (*Gossypium* spp.) plays an important role when studying linen textiles after medieval times.

Flax, hemp, nettle and even cotton textiles have or can have similar haptic and visual properties. This research project involved identifying methods to distinguish between those materials and to give a voice and history to those individual plants and their uses. Formerly, they were bundled under the term *linen* textiles.

I created a three-stage procedure for using microscopy methods to identify bast fibres, which is the core of this doctoral thesis. The results of this study are based on the application of this procedure to textile samples of various ages and conditions. First, I created a functional combination of methods with modern reference fibres based on their longitudinal characteristics, results obtained from the modified Herzog test and cross-sectional shape work as mutually exclusive characteristics that allow such identification. Heritage cotton fibres have their own challenges in terms of identification. Thus, I experimented with different identification factors to identify species-specific characteristics. In addition to

optical microscopy methods, other natural scientific tools of analysis were tested for their potential at identifying heritage cotton fibres.

The results are always subject to discussion and debate due to the fact that they include subjective interpretations. They indeed should be discussed, but such discussion is indicative of the state of the field at the moment. Giant steps have been taken already from the standpoint of making the methodology more transparent. Repeatability is the norm for contemporary research, and it can only be achieved by openly discussing methods, equipment and interpretations.

Discussions about post-colonialism, decolonisation and repatriation have increased greatly in the past few years in Finland and elsewhere throughout the world (Nylander, 2023; Snellman, 2021; Talja, 2021; Vainonen, 2019). I have welcomed such discussion, viewing it as a sign of societal progress and a way of promoting equality in the world. It is about time that oppressed nations and Indigenous peoples regain the rights to their intangible and tangible heritage. On the other hand, this raises fundamental questions addressed already in an article by Harlin (2019) about how such a stance may compromise my position as a researcher. In the context of the resent Sámi exhibition Mäccmõš, maccâm, máhccan (The Homecoming), which promoted the need to repatriate Sámi collections to the Sámi Siida museum, the National Museum of Finland (2021), which possesses many Sámi artifacts, quotes on its webpage the words of Petra Laiti:

> "Now, these objects will return home to where they are truly understood and where their heritage value can be correctly interpreted."

Even though I employed a strong post-colonialist research approach (Lahti, 2022) in **Paper II**, wanting to give a voice to a series of forgotten White Karelian textiles, I still wrestled with the question, who am I to study them? I have no White Karelian blood running through my veins. According to my utopian view of the world, we should all have an equal right to appreciate and study the material heritage of different peoples, and by studying the heritage of the White Karelian people, now a part of Russia, I am in no way wanting to imply that their heritage is again being taken away from them by someone else and owned by another, which only leads to hostility and discrimination towards non-members of the community. Rather, the heritage should be equally shared with everyone. Everyone should have the right to enjoy and interpret culture and heritage, from their own standpoint. After all, being born into a community does not make one an expert on, for example, craft skills or a type of dress that disappeared from use decades or even centuries ago.

2 Framing the research

2.1 Craft science

Craft science, or craft studies, is a relatively new discipline, established in Finnish universities in 1992. It can be seen as an umbrella definer for all researchers studying design and the making and use of craft objects. The research focus of craft science encompasses different forms and areas of craft, including design makers, design and making processes, and the study of products from psychological, physical, social, cultural, economic or technological standpoints (Luutonen et al., 1999).

Craft science applies many methodologies, with the theoretical paradigm informing craft science positioned at the crossroads of science, art and technology (Luutonen et al., 1999). The discipline does not have its own theoretical framework — methods and theories are applied according to the chosen approach. Luutonen et al. (1999) as well as Seitamaa-Hakkarainen et al. (2007) have provided visual representations of the different orientations of craft science (Figure 1). My research incorporates both cultural historical and applied science approaches, utilising theory derived from ethnography, history, archaeology, museology and the natural sciences. Most of all, the theorical framework has been adapted from object studies and heritage science. The study of objects does not fit into any particular discipline but represents instead a multimethodological viewpoint. As a much older research orientation than craft science, a multimethodological theoretical approach is best suited to addressing my research questions. I have, though, taken it one step further by combining material identification with a deep reading of objects, thereby obtaining deeper knowledge of and answers to the broader questions of origin as well as relevant agricultural and cultural connections. This approach is encouraged by heritage science.

Luutonen et al. (1999) sees the multimethodological approach as a strength for craft studies, though it is quite demanding. It requires the researcher to adapt in a versatile manner to the requirements of the research question. In my opinion, the main advantage of studying craft science is that it gives students the ability to learn new skills quickly and effectively. As Salo-Mattila (2014, p. 198) puts it, craft science offers a great possibility for the multidimensional study of textile culture when the researcher has first-hand experience with design and manufacturing

processes. This versatile type of expertise is an asset compared to other, less multimethodological, ways of researching textile culture.

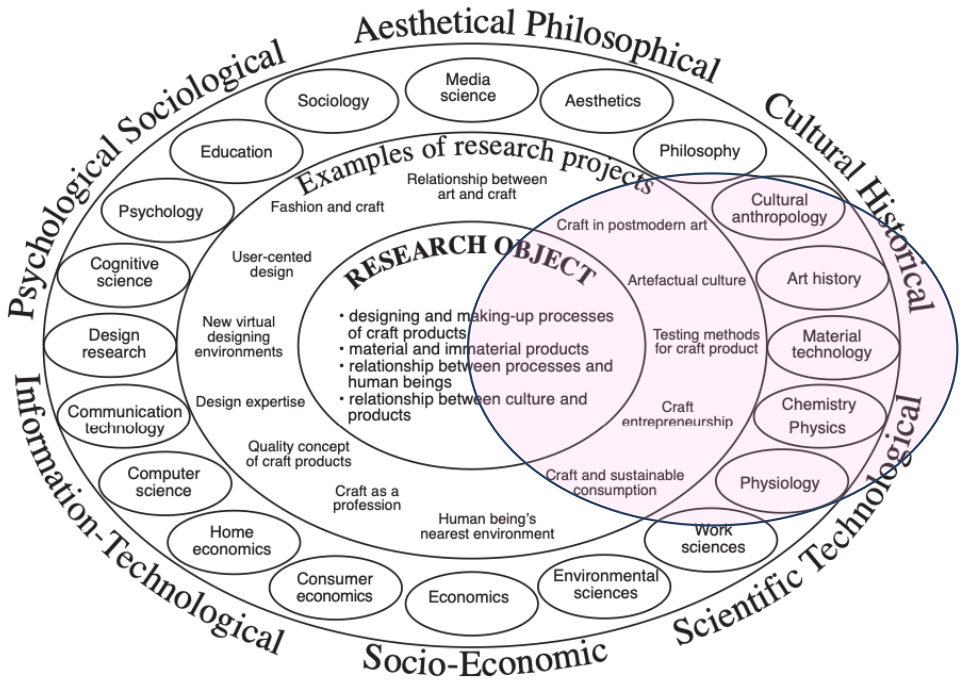

Figure 1 The relationship between different components of craft research, according to Luutonen et al. (1999), with the research focus and positioning of this research approach marked with a coloured oval.

In a more recent work on mapping craft science's methodologies in the Nordic countries, Kokko et al. (2020) have further developed the orientation of the discipline. Craft science first emerged in the 1990s as a discipline in Finland, Sweden and Norway, but the approach has varied among the countries. It has been invigorating to note that, in the Finnish context, we might have to broaden our view even more to include, for example, gardening within the spectrum of craft and subjects worthy of study as a part of craft science. My PhD research is mentioned in the study by Kokko et al., with the authors classifying it under the heading of *craft amplification* due to my use of applied science methods to identify fibres. A similar type of an approach utilising applied sciences has been presented by, for example, Räisänen (2014), who uses experimental research as a craft science method.

2.2 Material culture and object studies

Material culture refers to all objects, artefacts or items that are manufactured or altered within a culture (Harvey, 2017). They can be studied purely as objects or in a broader context by concentrating on the nature of materiality or the social aspects related to it — beliefs, values, ideas and assumptions (Harvey, 2017; Prown, 1982).

From a theoretical standpoint, this idea is more fully explained by Karen Harvey in the introductory part of a book entitled *History and material culture: a student's guide to approaching alternative sources* (2017, p. 2), where she provides theoretical classifications of the different types of object-based studies by Bernard Herman. **Object-centred** study can be categorised in several ways, either by concentrating on its physical attributes or from an art historical perspective, where the emphasis is on the emotional or psychological dimensions of material culture. **Object-driven** study, on the other hand, regards 'objects as evidences of other complex social relationships' (Salo-Mattila, 2014, p. 194). Salo-Mattila (2014) introduces another way to classify textile culture by dividing it into **material-driven** or **question-driven** research, based on the specific interests of the researcher.

Craft science has its origins in material culture studies and object-based research. Elsa Silpala (1990), in an article in the journal *Artelogi*, concisely explains object-based studies theory within the context of craft science. At that time, a prevailing school of thought or trend in Finnish *arteology*, which can be thought of as one of the ancestors of craft studies, involved analysing the external properties, internal properties and material aspects of an object, an approach that '*can be directed all the way to the chemical properties'* of an object (Silpala, 1990, p. 18).

More researchers of late have been conducting Finnish textile-related, object-based studies. Examples include doctoral research by Fernström (2012) on designer culture and Dora Jung's damasks and Koskennurmi-Sivonen's (1998) study of design and artefacts in a Finnish fashion house context. Aikasalo (2006) has given voice to museum textiles and collections as research material. Again, Salo-Mattila (2000) has done vast cultural history research on the Empress screen, a beautifully embroidered dressing screen given to the Empress of Russia in 1885. Vartiainen (2014) has documented the importance of artefacts for history enthusiasts. Sipilä (2012) has studied aprons using methods from cultural history, gender studies and hermeneutics. For his part, Lehtinen has done extensive work on folk costumes as well as Finno-Ugric kindred nations, their clothing and accessories (Lehtinen, 1999; Lehtinen & Sihvo, 1984). Some research has also been done on how prominent figures dressed, like Jean Sibelius (Kaipainen, 2017) and Elias Lönnrot (Snellman et al., 2018). All these studies are good examples of the different kinds of research possible when adopting a textile-related, object-based approach.

Next, I summarise some theoretical models for object studies relevant to my own research, which I already introduced for the first time in my master's thesis in the

field of South Asian studies (Suomela, 2020). To systemise the study of object-centred research, various researchers have contributed to developing a clear theoretical approach. Caple (2006), for example, has created an investigative model referred to as FOCUS (formalised object construction and use sequences). This model is intended especially for studying archaeological artefacts and encourages a more formalised reporting of the findings instead of brief and inaccurate descriptions laden with academic jargon.

Flemming's (1974) well-known model draws attention to a series of five properties and four operations informing object studies: **history**, **material**, **construction**, **design** and **function** comprise the properties, whereas **identification**, **evaluation**, **cultural analysis** and **interpretation** comprise the operations (Figure 2). Severa and Horswill (1989) have modified this model, making it more suitable for analysing a dress as an artefact. Their version includes **material**, **design and construction**, and **workmanship** properties (Figure 3). Interestingly, they failed to include history as a property, arguing, rather fairly, that in very few cases can an artefact's history, and accordingly its dating, be unreliably concluded when textiles are in question.

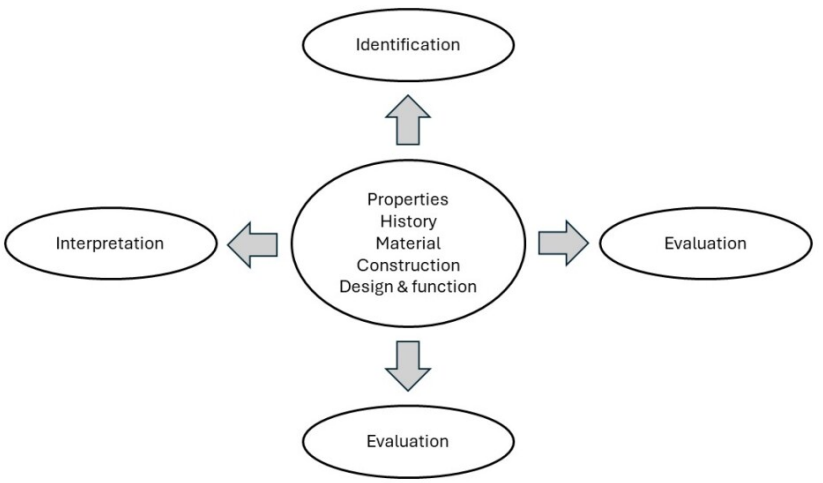

Figure 2 Visualisation of Flemming's model (1974) for an object-based study (J. A. Suomela).

In Severa and Horswill's (1989) model, the **design and construction** properties of an artefact, the dress, should be divided into sub-sections consisting of **basic elements**, including bodice, sleeve, and skirt. They also note the **importance of focusing on places where the elements intersect**, including the shoulder, waist, armscye and sleeve joint. **Workmanship** is again divided into subsections involving **treatments**, which include seam finish, shaping method,

fullness control and hem technique; finally, they call attention to the **level of skill** in selecting materials, cutting them, finishing them and their effect. All three properties, **material**, **design and construction**, and **workmanship,** should be examined via the four operations of **identification**, **evaluation**, **cultural analysis**, and **interpretation and intuitive analysis**. While the nature of each property is clearly conveyed by its name, the operations are more difficult to construct and implement. **Identification** includes providing a detailed description of all aspects of the object, from manufacture to wear. Even though **evaluation** overlaps with **cultural analysis** and **interpretation**, it can be understood simply as aesthetic value. During **cultural analysis**, the object is placed in its original surroundings and various aspects of it are taken into consideration during the product analysis and content analysis phases. Interpretations require careful consideration of the object's cultural context. **Intuitive analysis** allows researchers to express their own subjective feelings regarding the object.

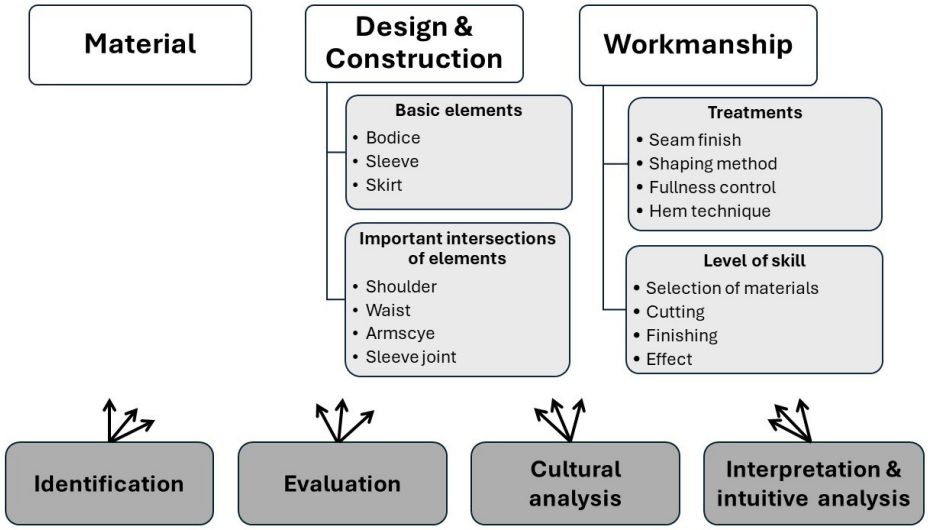

Figure 3 Visualisation of Severa and Horswill's (1989) model for object-based research on dress (J. A. Suomela).

Pearce (1994) has devised a model for studying especially archaeological objects based on Flemming's prior work. She reminds us that we should be able to ask questions of *how, what, when, where, by whom and why* to achieve useful answers regarding the role of objects in social organisation (Pearce 1994, p. 126). In her opinion, Flemming's model is problematic, though, in terms of its operations approach. She instead proposes an eight-step model divided into the areas of **material, history, environment** and **significance**. In the first step, the

material, **physical** and **descriptive** characteristics of the artefact are recorded. In the second step, the artefact's physical attributes are compared with existing ones to create typologies. In the third step, the researcher looks for corresponding examples of provenance and technique. In forth step, the researcher should focus on the object's **history**, including its dating and lifecycle as well as its practical function. The fifth step involves assessing its **environment** at the micro and macro level — knowledge recorded in situ and in surrounding locations. The geographical aspects of an object's **environment** are dealt with in the sixth step. The seventh step pertains to its **significance,** that is, the emotional and psychological messages that the object carries with it. Pierce emphasises the need to consider the significance of the object in its own time, which quite often differs from our perspective. Finally, th eighth step involves combining all the knowledge gathered during the previous steps to offer an interpretation.

Mida and Kim (2015) have published a more recent model for studying dress in object-centred research, which can be applied to analyses of ethnographic material as well. They base their model on the famous work of Jules Prown (1982). His model includes three stages of object analysis, with the analysis moving from **description** to **deduction** and finally to **speculation** (Figure 4). The **description** stage includes **substantial analysis**, which can be understood as physical measurement and description of the object, materials and fabrication of the object, i.e. how the object was manufactured and what techniques were used. After that, the description moves to **content analysis**, which focuses on the visual motifs of the object, and finally to formal analysis. **Formal analysis** is easier to understand when it is turned the other way — analysis of the object's form. What forms, textures and colours can be detected?

In the **deduction** stage, the artefact is observed from the user experience point of view, or in Prown's (1982) own words, it involves observing '*the relationship between the object and the perceiver*', or 'what it would be like to use or interact with the object'. It includes **sensory engagement** (whenever the object is accessible) as well as **intellectual engagement**, which can be understood as what facts the researcher can deduce after studying the object. Prown (1982) gives an example in his article of a pictorial object and encourages researchers to observe, for example, what time of the day it is or the effects of natural forces. In the case of textiles, these questions are quite different, though. The final part of the deduction stage is **emotional response**. Severa and Horswill (1989) have also included this idea in their model, giving it the name intuitive analysis. In qualitative studies, researchers cannot be outsourced and their own subjective force must be acknowledged.

In the **speculation** stage, the researcher creates **theories and hypotheses** — the object is interpreted based on understandings of the culture that fabricated the object. The **programme of research** step ties external knowledge to the

object. Reference material and literature are combined according to the researcher's interests.

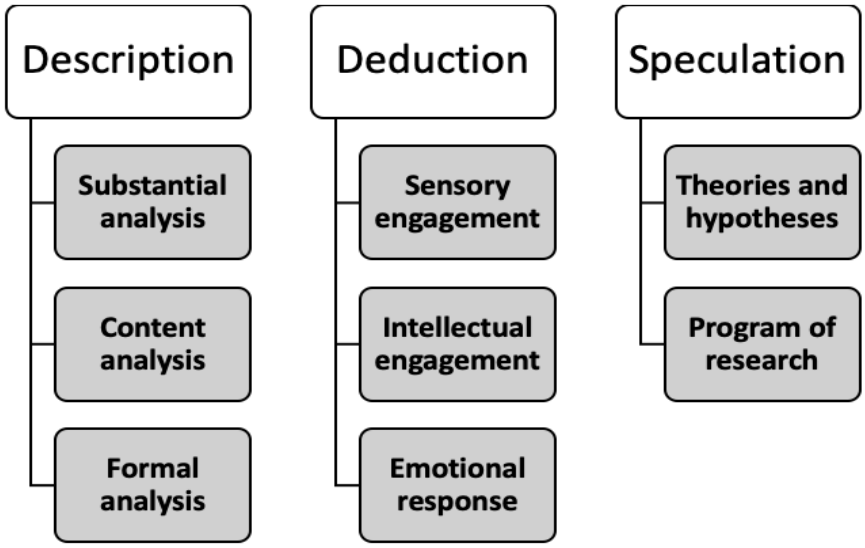

Figure 4 Visualisation of Prown's (1982) model for an object-based study (J. A. Suomela).

Mida and Kim's (2015) model has the same three-stage structure as Prown's model (1982). Their central categories of analysis are **observation**, **reflection** and **interpretation**, with a supplementary checklist to facilitate the analysis (Figure 5). They refer to the observation stage as a **slow approach to seeing** the object, meaning 'looking carefully and thoughtfully' at it (Mida & Kim, 2015, p. 29). They suggest drawing as a means for making sharp visual observations. It forces researchers to concentrate on the object and enables them to memorise details that might not be recorded in photos.

Mida and Kim (2015) propose a more comprehensive phase of reflection in place of Prown's (1982) deduction stage. Similarly, it includes **emotional and sensory engagement**, and it works on an intuitive level. In Mida and Kim's (2015) model, the process of gathering and analysing the sources of contextual material belongs to this stage. Provenance records, reference items in other collections, supporting images and textual material, among other things, are valuable sources for reflective analysis. Additionally personal observations are welcome in this stage.

In the **interpretation** (corresponding to Prown's (1982) speculation) stage, the information collected from the object and from the source materials are connected. In the case of dress, Prown's (1982) model is at this point often problematic; hence, Mida and Kim (2015) propose an alternative course of action. In their vision, the

interpretation should be more creative and versatile depending on the interests of the researcher.

The questionnaire checklist for the **observation** stage includes forty comprehensive questions divided into six sub-sections. The **general** section includes questions about the sex of the user, labels, dominant colour or patterns, and the condition of the object. The **construction** stage includes questions about the object's structure — its measurements, whether sewn by hand or machine, pockets or lining, and so forth. In **textile**, questions are about material, finishing, and surface decorations. **Labels** provide information about the maker. **Use, alteration and wear** concentrate attention on any modifications or possible damage to the dress. Photographs, provenance, receipts and other additional material are dealt with in the **supporting material** phase of the study.

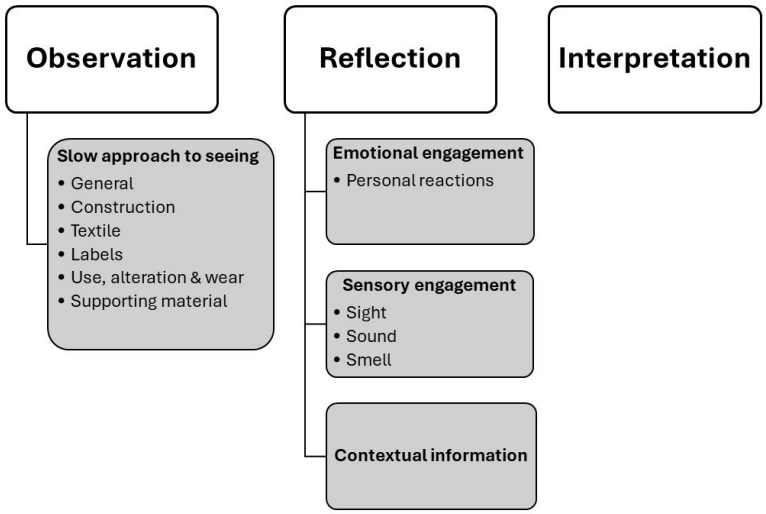

Figure 5 Visualisation of Mida and Kim's (2015) model for object-based research on dress (J. A. Suomela).

In my own work, I have used all of these models and approaches as theoretical framework to focus my attention on meaningful issues pertaining to an object. At the macro and micro levels, they have guided me towards a more holistic view and understanding of the object. Numerous models exist for conducting object studies of textiles beyond the ones presented above. What I see as a uniting theme in all of them is that the object is voiceless and without context. I have not closely followed any of the models in my papers, but instead have included their versatility in my approach. Even though the main focus of my study is material identification, the results are meaningless without a broader cultural and societal context.

2.3 Heritage science

In 2006, the Science and Technology Committee of the Parliament of the United Kingdom published a report entitled 'Science and Heritage' that discussed the current state and future management of the nation's cultural heritage (House of Lords Science and Technology Select Committee, 2006). At the same time, the committee re-introduced the term 'heritage science' to cover a broader perspective on heritage research, than formally known as conservation science. The term heritage science had reportedly first been used in 1843 by Michael Faraday in his Royal Institution Christmas Lecture (Nanetti, 2021). Whatever the truth, the report gave the term new life and a starting point for a newly evolving discipline.

Cosentino (2016, p. 1) defines Cultural Heritage Science (CHS) as offering a way to 'examine works of art and archaeology by means of technical and scientific methodologies to understand when and how these artifacts were made, and, as well important, how are they to be preserved, what conservation treatment represents the best option and why'. It is an umbrella term for all relevant fields of science seeking to study cultural heritage, including all possible fields ranging from humanities to artificial intelligence, from arts to engineering sciences and from classical chemistry to physics and biology. Depending on the author, it is defined as a multi-, inter- or cross-disciplinary field that is still evolving and finding its ultimate form (Cosentino, 2016; Nanetti, 2021; Strlič, 2018).

The main aim of heritage science is to understand, interpret and safeguard our cultural heritage using modern scientific methods. For example, one futuristic aim lies in its preference for non-destructive or micro-destructive testing (Kennedy, 2015, p. 221). This multifaceted approach to understanding historic and archaeological objects and textiles has guided my research substantially in addition to object studies theories.

2.4 Fibre identification methods for plant fibres

Textile fibres can be identified using multiple methods based on their physical, chemical or genetical properties. Natural and synthetic fibres all have some distinctive characteristics that allow them to be identified at least at the level of fibre type. My study is mainly based on the distinctive characteristics that can be identified in the visual properties, or morphological characteristics, of a fibre sample. In this section, I introduce common identification methods suitable for studying cellulose-based fibres, starting from simple and easy methods and proceeding towards more sophisticated methods that require costly equipment and expertise on the part of the user.

2.4.1 Basic methods

The most straightforward method for identifying fibre types is a burning test, where the smell, ash and behaviour of the fibre bundle is observed near a flame (Nayak et al., 2012, p. 320). Slightly more accurate results can be achieved with a solubility test, where the fibres are exposed to several solvents and fibre types are identified based on their dissolution behaviour (Garside, 2022, p. 375). The Shirlastain staining test belongs to the same category as the previous methods – in this case, the material is dyed using certain chemicals, with the fibre type being dependent on the shade of the dyeing result (Greaves & Saville, 1995, p. 17). All these test methods are based on the chemical properties of the fibres, but they allows for identification only at the most general level (Garside, 2022, p. 375; Greaves & Saville, 1995; Nayak et al., 2012, p. 314).

One parameter for identifying bast fibres is the orientation of the microfibrils. A simple way to study their orientation is by conducting a drying twist test (Perry et al., 1985, p. 225). The fibre, at a length of at least a few centimetres, is held over a hot plate until it starts to twist, and the orientation can then be observed according to the direction.

With these simple identification methods, though, the destructivity of the bast fibres and the large sample sizes needed are problematic, meaning they are not recommended for studies of heritage textiles. Based on the aims of heritage science, the objective should be non-destructive testing, or if that is not possible, then the smallest possible sample size.

2.4.2 Optical microscopy methods

In optical microscopy, the fibres are typically observed with a transmitted light microscope (TLM), either using longitudinal or cross-sectional positioning. Physical fibre characteristics in a longitudinal direction that can be utilised in the identification process include the fibre's cross markings, dislocations or convolutions (Catling & Grayson, 1982; Greaves & Saville, 1995; Rast-Eicher, 2016). With cross-sectional positioning, the observed fibre shape, the shape and size of the lumen, and the thickness of the cell wall are of interest. Using polarized light microscopy (PLM), it is possible to observe the orientation of the microfibrils with the aid of the modified Herzog test (Haugan & Holst, 2013). The presence of calcium oxalate crystals can also serve as an identification parameter because, contrary to other bast fibres, flax plants do not produce those crystals (Bergfjord & Holst, 2010). These identification parameters will be discussed more thoroughly in section 6.3.

Researchers have previously experimented with a fibre's length and width as well as the fibre end morphology in the hope of identifying distinguishing characteristics of bast fibres, but with no success (Bergfjord et al., 2012; Catling &

Grayson, 1982; **Paper I**). The versatile natural variation among fibres means that it is useless to concentrate on such parameters.

Optical microscopy demands sample taking, but at a much smaller scale than in the tests mentioned in the previous section. Carefully prepared glass slides with permanent mounting media, for example Entellan™ new, makes it possible to store fibres and study them with optical microscopy for a very long time.

2.4.3 Other equipment-demanding methods

A scanning electron microscope (SEM) is widely used to study fibres (Rast-Eicher, 2016). Its imaging creates a detailed depth-of-field view of the sample's surface at a high resolution. This observation method is rarely useful when identifying plant fibres because meaningful differences in bast fibres often lie in areas other than their surface morphology.

Another electron microscope method that is widely used in science is transmitted electron microscopy (TEM). It allows for observation of thin sections of the specimen's ultrastructure (Reza et al., 2015). This method is overly sophisticated, though, for identification purposes, as it takes much time and effort to prepare the samples. Nevertheless, a cross-cutting method developed from a TEM sample preparation procedure is introduced in **Papers IV** and **V**.

One possibility for measuring the chemical properties of fibre material is to use a spectroscopy method, such as Fourier-transform infrared spectroscopy (FTIR) or Raman spectroscopy (Edwards & Wyeth, 2005; Nayak et al., 2012, pp. 333–337). These optical spectroscopy methods measure the reflectance of certain wavelengths generated by chemical bonds in the studied substance. The problem in this respect is that bast fibres are chemically composed in a similar manner and significant differences are difficult to detect. According to Garside and Wyeth (2003), Attenuated total reflection (ATR), when used in conjunction with FTIR, should make it possible to detect differences in complicated calculations, but it demands sophisticated equipment and strong expertise on the part of the researcher. Natural variation, harvest time and the degradation stage might also hinder the interpretation of these results (Nayak et al., 2012, p. 334). FTIR and Raman spectroscopy do though offer certain distinct advantages in fibre and textile studies because the methods are non-destructive and, in the best cases, require no sample taking.

3 Research questions and aims of study

In my doctoral research, I have concentrated on developing methods for identifying plant fibres and applying that knowledge to comprehensive interpretations of heritage linen textiles. The three-stage procedure, introduced in **Paper I**, has formed the core of this thesis, and all the papers focus on testing the procedure for fibre samples of various age and conditions. The aims have been structured based on a theoretical frame informed by craft science, object studies and heritage science. Understanding concepts like linen, linen materials, linen textile structures and craft practises as well as their relevance and how to place linen textiles in various cultural contexts have been at the centre of this study. The timespan, ranges from the Late Iron Age (800–1150/1300 CE) to the late 19th century, and the geographical context is the current area of Finland extending eastwards to White Karelia and the kindred Finno-Ugric nations of Khanty and Mansi in contemporary Russia.

The research questions of my thesis have been formulated as follows:

1) What is the feasibility of the three-stage procedure for bast fibre identification?
2) How can X-ray spectroscopy and tomography methods contribute to material identification or other technical interpretations of heritage linen textiles?
3) How has the term 'linen' been defined, and what do the interpretations reveal about its cultural context?
4) How can the knowledge gained from heritage science methods be utilised in the study of heritage linen textiles from the broader standpoint of object studies and textile history?

4 Linen textiles in a Finnish context

It is important first to define just what the terms linen and linen textile mean within the context of craft and heritage science and object studies. In this thesis, including **Papers I–IV**, linen is used as general term for all usually undyed, tabby-woven material originating from plants. The terminology issues are more widely discussed in section 8.2. Other characteristics generally addressed in the study of linen textiles include, on the one hand, their lightness, shininess, whether they remain cool in hot weather and their durability, and on the other whether they wrinkle easily, whether they are difficult to dye with natural dyes and if they are inelastic (Räisänen et al., 2017).

While different fibre plants are easy to recognise based on their visual appearance, the characteristics of fibres are similar and different fibres are difficult to distinguish from each other. Even within a single species of bast fibre plant, variation occurs due to the growth conditions. Contemporary identification methods are based on the exclusive combinations of fibre characteristics (Hughes, 2012, p. 602).

4.1 Ethnographic and historical textiles

Based on museum collections and estate inventory deeds, it is evident that linen textiles have had a wide range of uses, from bedlinens and towels to undergarments and clothing items and laces and decorative items. Coarser linen again has been used for sacks and sails as well as ropes and strings.

4.2 Archaeological textiles

In an archaeological context, though, demonstrating the use of linen is not so straightforward a process due to a lack of direct evidence. Plant material survives poorly in the acidic Finnish soil, and actual linen textile remains have survived only since the Late Iron Age, around 1000 years ago (Riikonen, 2011). Apart from a few cordage and fishing net finds from the Stone Age (8850–1900/1700 BCE) (Kujala, 1948; Miettinen et al., 2008), when seeking to determine the earlier usage of linen material remains assumptions must be made based on secondary evidence, such as plant macrofossils, pollen, and cord impressions on pottery (Hardy, 2008).

In her article 'White linen: cloth of luxury', Riikonen (2011) lists almost 70 archaeological plant fibre finds from various sites in Finland, mostly from the Late Iron Age or Crusade period (10th to 13th centuries), that hint at the use of plant materials in garments, wrappings, weaponry and embellishments (see also **Paper IV**).

4.3 Linen materials

4.3.1 Flax

Flax (*Linum usitatissimum*) was domesticated more than 8000 years ago in the Fertile Crescent region (Karg, 2011). Pollen and plant macrofossil analyses suggest a relatively late use in Finland, only since the 5th century CE (Aalto, 1982; Seppä-Heikka, 1985; Tolonen, 1978, p. 196; Vanhanen, 2020; **Paper IV**).

Soil and climate conditions throughout the Finnish peninsula are suitable for flax cultivation, and it has long been a popular crop in southern parts of the country. Tax records from the year 1500 reveal that already then, flax production was being taxed in Karelia by Novgorod (Ronimus, 1906, p. 65). In the 17th and 18th centuries, the Swedish Kingdom collected taxes in the region as well. After the mid-18th century, flax cultivation dropped dramatically in Karelia, being replaced with hemp (Manninen, 1922, pp. 106–107). The western areas of Finland experienced noticeable flax production from early on. Already in 1529, records mention flax tabby as an important good exported from Turku. Commercial weaving was clustered mainly in Turku and Porvoo, peaking around the mid-18th century (Virrankoski, 1963, pp. 53–54).

By the start of the 19th century, the province of Tavastia (Fi: Häme) had become the centre of the flax trade. The amount of commerce can be perceived from statistics for the years 1816–1841. It has been estimated that Tavastia sold flax fibres annually at an amount of 60,000–150,000 *leiviskä* (sw. *lispund*; 8.5 kg), which in modern mass measurements would be in the range of 510,000 to 1,275,000 kilograms (Virrankoski, 1963, p. 23). Flax was exported especially to Sweden in noticeable amounts. In 1830, the Turku customhouse exported almost 300,000 *kyynärä* of tow cloth (Sw: *aln*; Eng; ell; in the times of the Grand Duchy of Russia, the length was 71.12 cm), in modern length measurements 210 km (Virrankoski, 1963, p. 103). The cotton industry, which began in the 1850s, slowly put an end to flax production as a Finnish cottage industry. Industrial-scale flax production did exist though in the 20th century, for example as fine damask cloth from the Tampella factory (Fernström, 2018). Unfortunately, the last linen factory, Oy Ahlmdahl Ab, to process flax fibres closed in 2003. Now, when the textile industry is slowly reviving in Finland, hopefully fibre plant cultivation and related activities will recover as well (Suomen Tekstiili & Muoti ry & Owal Group Oy, 2022). For

example, Taitoliitto launched in the summer of 2022 a 1 m2 flax project that concentrated on reviving flax as a heritage plant (Taitoliitto, 2022).

4.3.2 Hemp

The origin of and timespan for the use of hemp (*Cannabis sativa*) is still debated. The latest genome resequencing-based research pinpoints the time of its domestication at 12,000 years ago, in East Asia (Ren et al., 2021).

Hemp was not cultivated or used so much in the western coastal areas of Finland, but in the area of Tavastia (Häme) hemp, and not flax, was taxed throughout the 16th century. In the 17th century, both were influential trade products in the area. Hemp was still used in the 19th century, but it was often imported from Russia, which produced better quality hemp (Virrankoski, 1963, p. 127).

Hemp was likewise taxed in North Karelia during the 17th century and afterwards, and by the late 18th century it was preferred over flax in eastern Finland for clothing and linen textiles (Manninen, 1922, p. 108). In western parts of Finland, hemp was used for coarser purposes than flax, especially for fishing nets, sails, bedlinens, strong sewing yarns and ropes. In eastern Finland, it had a wider range of use, from fishing gear to fine underwear, towels and garments (Kaukonen, 1946, pp. 37–38).

4.3.3 Nettle

Nettle is the only fibre plant indigenous to Northern Europe. Kaukonen (1946, pp. 23–25) and Geijer (1979, p. 9) both note uncertainty and lack of knowledge regarding when nettle was first utilised as a textile plant. Kaukonen (1946), Hald (1942) and Rodenstam (1918) all present convincing records from historical times about the use of nettle, but the prehistoric record is still quite vague. Historical records make some mention of nettle as a textile material in Finland, but ethnographic questionnaires from the early 20th century reveal that all knowledge of the tradition had been lost by that point (Kaukonen, 1946, p. 25). Archaeobotanical records are useful for research on the distribution of cultivated plants, but useless with respect to nettle, which was already present in early prehistory and grows wild. In an effort to pinpoint one of the earliest use contexts, Korkeakoski-Väisänen (1993, p. 22) suggests that nettle yarn might have been used as a decorative impression on a Corded Ware pot found in Piikkiö, in southwestern Finland — the Corded Ware culture was present in southern Finland around 2500 BCE. Due to the difficulty of identifying aspects of Corded Ware culture, the archaeological records are still meagre and/or often unreliable (**Paper IV**).

Bergfjord and Holst (2010) discovered and successfully identified a fragment of nettle textile at Lusehøj, in Voldtofte, Denmark. They dated it to 2 800 years after the Bronze Age (c. 1750–500 BCE in Fenno-Scandinavia), with strontium isotope analysis confirming that it had been imported (Bergfjord et al., 2012). It is worth mentioning that archaeological periods occur at slightly different times based on the geographical location of the site. For example, the Bronze Age occurred in Central Europe at around 3300 to 1200 BCE, whereas in Finland it began as late as approximately 1500 BCE. In the Finnish context, the earliest nettle and other bast fibre textile finds (excluding tree bast finds, such as Antrea's net) date to the Late Iron Age (Miettinen et al., 2008; Riikonen, 2011; **Paper IV**).

More than thirty different plants have been defined as nettle around the world. In Finland, three different species or subspecies are recognised: *Urtica dioica*, stinging or common nettle, *Urtica dioica sondenii*, which is a subspecies of it, and *Urtica urens*, annual nettle (Hukkinen, 1991, pp. 2–5). Internationally, the more common nettle plants include ramie (*Boehmeria nivea*) and Himalayan nettle (*Girardinia diversifolia*), also known by its local name '*allo*' (Dunsmore, 1993, p. 59; Perry et al., 1985, p. 18).

4.3.4 Cotton

The use of cotton in textiles independently emerged almost simultaneously in both South Asia and South America. The earliest South Asian cotton textile finds are from the Indus Valley, in present-day Pakistan. Based on their cross-sectional characteristics, Moulherat et al. (2002) identified cotton yarn inside of a bead that was excavated from Mehgarh, in Pakistan, and dated to 6000 BCE. Another famous, though controversial, cotton find is from Mohenjodaro, also in present-day Pakistan, and it has been dated to 3000 BCE (Gulati & Turner, 1929). This find is lost since, and hence unobtainable for modern research methods. Resent publication from Splitstoser et al. (2016) reports cotton finds from coastal Peru from the same time period (4900 BCE).

The earliest documented cotton finds from Finland are from the 14th century, discovered at Turku Cathedral (Arponen, 2015; Arponen et al., 2018; Karttila, 2014). Recently published finds from Oulu Valmarinniemi, in northern Finland, date to the 14th century (**Paper III**), while the Masku intarsia textile, dating to the 15th century, was discovered at the Nådendal Abbey (Wright et al., 2023) and a rug-paper and tabby (probably from a shirt) were discovered underneath the floor of a seventeenth-century church in Oulu Hailuoto (Suomela & Lipkin, in press).

Estate inventory deeds show that cotton gained in popularity as clothing material in the 18th century (**Paper III**). Especially after Finlayson's cotton factory opened in 1835, cotton started to supplant other plant fibres for general use (Virrankoski, 1963, p. 141).

5 Research material

5.1 Context and chronology of studied plant fibre artefacts

The geographical context of the research material used in this thesis is the peninsular area in the north Baltic Sea currently known as Finland. Finland is a relatively new country that declared its independence in 1917. Before that, in the years 1809–1917, the area was part of the Russian Empire and known as the Grand Duchy of Finland. In 1809, Sweden had lost the Finnish territory to Russia, an area it had controlled since the Crusade period in the 12th century.

The research material in **Paper I** is an exception to the other data used for the study. The majority of the research material in that paper derives from kindred Finno-Ugrian nations in Siberia, the Khanty and Mansi peoples. Most of the material was collected in the 19th and 20th century. The rest of the textiles discussed in the paper are from the Historical Collection at the National Museum, with an unknown origin, although with indications that they originated in Central Europe. The apron (H5633:10) has been dated to the early 18th century, but geographically its place of origin is vague (Pylkkänen, 1970, pp. 308–309, 445).

Paper II focuses on geographically intact material. All the textiles were collected from White Karelia in 1894. Most of the material dates to the 19th century, with a few exceptions containing context information that points to the 18th century. Here, it must be pointed out that White Karelia has never been part of the Finnish nation, but during the late 19th century the followers of a Finnish-inspired Karelianism Movement promoted it as the cultural cradle of the Finnish people (Sihvo, 1969).

In **Paper III**, the research material consists of archaeological cotton finds from fourteenth-century Valmarinniemi, a delta area of the Kemijoki river, in northern Finland; a fifteenth-century Masku intarsia textile manufactured at the Nådendal Abbey, in southwest Finland; and seventeenth-century finds from Hailuoto Church in the coastal part of Oulu, also in northern Finland. In addition to these finds, White Karelian cotton textiles, also addressed in **Paper II**, are discussed in the study.

The research material analysed in **Paper IV** is from Ravattula Ristimäki, near Kaarina, in southwestern Finland. The material dates to the Late Iron Age, around

the 12th century, and is the oldest material discussed in this thesis. **Paper V** is a purely technical study of cross-sectioning and does not include cultural connections. Figure 6 shows the chronology and geographical locations of the research material.

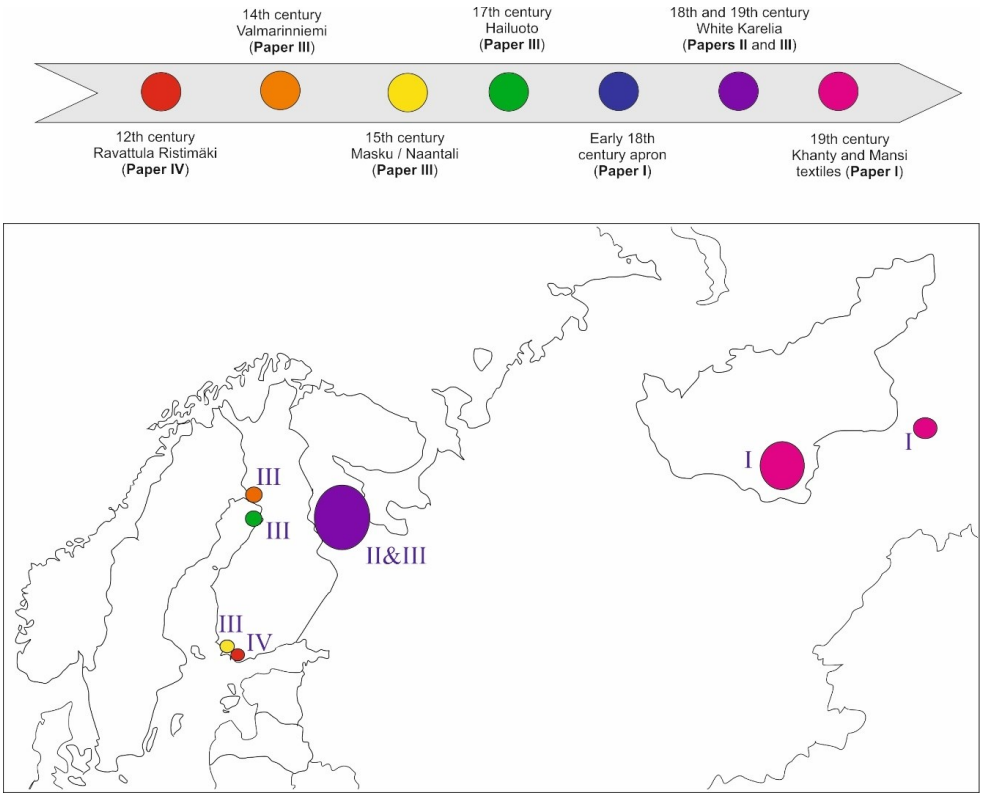

Figure 6 Timeline and geographical locations of the research material.

5.2 Museum textiles from Historic and Finno-Ugric Collections

The textiles studied in **Paper I** were curated by the now retired intendent of the Finno-Ugric Collection at the National Museum, Ildikó Lehtinen. Upon my request, she chose 12 textiles from the museum's collections (Table 1). Three of them were of unknown geographical origin from the Historic Collection, while the rest from Finno-Ugric Collection. The items from Finno-Ugric Collection were all collected in the late 19th century or at the turn of the 20th century. Three of them belonged to the Khanty people and five to the Mansi people. The upper part of a shirt, *rätsinä* (SU4522:18), belonged to the White Karelian Collection, which was used as research material in **Paper II**.

Table 1 Additional information about the research material in **Paper I**.

	Object number	Object	Origin	Date	Collector/donor
1.	H5633:10,	apron	unknown	early 18th century	unknown
2.	H65050:986	curtains	unknown	unknown	A. R. Enckell
3.	H70001:2	tablecloth	unknown	unknown	Commercial counsellor LIgnell
4.	SU1870:49	miniature of a fishing seine	Khanty	before 1877	August Ahlqvist
5.	SU3904:573	rabbit snare	Khanty	before 1899	Uuno Sirelius
6.	SU4518:125	offering cloth	Mansi	before 1905	Artturi Kannisto
7.	SU4518:126	unfinished offering cloth	Mansi	before 1905	Artturi Kannisto
8.	SU4518:127	unfinished offering cloth	Mansi	before 1905	Artturi Kannisto
9.	SU4518:128	unfinished offering cloth	Mansi	before 1905	Artturi Kannisto
10.	SU4518:129	unfinished offering cloth	Mansi	before 1905	Artturi Kannisto
11.	SU4522:18	upper part of woman's shirt	White Karelia	before 1894	I. K. Inha
12.	SU4810:283	woman's shirt	Khanty	before 1906	Artturi Kannisto

5.3 White Karelia

5.3.1 Textiles

Heading number SU4522 consist of White Karelian textiles and artefacts acquired by various collectors at the end of the 19th century. Most of them were gathered by I. K. Inha, apart from a few exceptions. Of the items in collection SU4522, item numbers 88–97 and 131–135 were collected by Uuno Karttunen; numbers 98–100, 106 and 136 are from local collector Iivo Marttini; and 87 and 127 were collected by Heikki Meriläinen. The probable reason for combining all these items under the same title number is that the objects have a similar frame and are from the same region. They were combined in the same collection already before being handed over to the museum in 1905, which is evident from the original old main catalogue possessed by the National Museum. For the sake of clarity, I limited the research material to the items collected by I. K. Inha (**Paper II**). The cotton textiles are included as research material in both **Papers II** and **III**.

5.3.2 Travel accounts and other literal documents

I. K Inha (1911) wrote a more than 400-page travel account of his trip to White Karelia. I read the book thoroughly and made notes on everything related to textiles. I processed the notes with Atlas.ti software, which makes it possible to code and annotate text.

Additionally, I consulted archival documents to better understand Inha's motives and the context and circumstances of his travels. The archives of the Finnish Literature Society (SKS) have stored his travel notes, his grant application and the minutes of the meeting where his proposed travels were discussed, and all the photographs he took on the journey. From the archives of Finnish Heritage Agency, I was able to find records, correspondence and minutes from the State Archaeological Commission for the year 1894, including the letter (no. 1427) where Inha offers the collection to the Commission for purchase.

5.3.3 Photographs

The photographs taken by I. K. Inha during his travels through White Karelia are found in the SKS archives — they are nowadays also publicly available through the finna.fi platform. Altogether, the collection consists of 219 photographs that were originally developed on glass sheets. Inha is well known for his landscape photos, but on this trip he concentrated on portraying people and documenting everyday life in White Karelia.

The photographs were also processed using Atlas.ti software, which allows for tagging pictures and even parts of them. So, it is possible to study, for example, all the photos that include female dress at once. The photos show people clothed in contemporary styles, and it is clear that Inha's collection policy was to document much older items. Nevertheless, the photos still provide contextual knowledge and cultural information.

5.4 Archaeological bast fibre samples from Ravattula, Ristimäki

Ravattula, Ristimäki Church and the surrounding cemetery from the Late Iron Age comprise an excavation site managed by the University of Turku's Department of Archaeology between the years 2010 and 2016. Grave findings were excavated mainly as larger soil plots, with the excavation findings finalised in laboratory conditions afterwards. I have only studied the bast fibre samples that archaeologist Jaana Riikonen, head of the laboratory work, provided me with from the excavation data.

5.5 Archaeological cotton finds

Recently, I have been part of several research papers where cotton has been one of the identified fibre types — they are discussed in **Paper III.** A small tabby fragment from the burial site of the Catholic church in Valmarinniemi, which burnt down at the turn of the 15th century, was identified as being made of cotton (**Paper III**). This excavated find, made already in the early 1980s, is from the same time period as the oldest ones found in Finland.

The Masku antependium, from the 15th century, is a famous ecclesial textile that has been the target of detailed research several times in the past (Aspelin, 1879; Nordman, 1943; Pylkkänen, 1974). It was manufactured by the Bridgettine Sisters at the Nådendal Abbey around the 1440s. In 2016, the materials were identified as part of a reconstruction project (Wright et al., 2023). The mostly woollen antependium contained small decorative pieces of cotton in the tails of the peacocks.

Hailuoto is a small island just off the coast of the city of Oulu. During excavations of the burnt church, some textile fragments were found underneath the floor. They were dated to the 17th century. A coin, an öre from the time of Queen Cristina, in the year 1667, was found wrapped in rug paper that was made of bast fibres and cotton. A small piece of cotton tabby had also survived in connection with a tin button (Suomela & Lipkin, in print).

5.6 Modern reference samples

To validate the methods, modern reference samples have also been included in the research material. I have collected nettle samples from nature since 2013. In **Paper I**, commercially manufactured bast fibres and yarns were used as reference material: the list can be found in the paper.

In **Papers I, III** and **V**, modern reference fibres were used for adjusting the methods. The reference fibres have different sources, including the University Botanical Gardens (cotton and bast fibres), commercial seed distributors in Etsy (cotton) and the samples collected from nature (nettle).

6 Methods of research

To quote C. Rogerson (2022, p. 5): '*Applied science is the use of scientific processes and knowledge as the means to achieve a particular practical or useful results*.' As much as I would want a magic box for fibre identification that would yield clear, quantitative, numerical results requiring no subjective interpretation, such technology is not yet available. When dealing with heritage material, many variables need to be taken into account and the judgement relies on the professionalism of the researcher, meaning that a holistic view is required to achieve meaningful results (Rogerson, 2022, p. 7).

To quote again from the same book:

> The information may help to: determine the provenance, history, use and adaptation of an object; characterise its composition, construction and state; identify the presence and effect of previous treatments; and inform future decisions about conservation, use and storage. This can be achieved through the identification of the materials used to construct the item, the nature of structural and microstructural features, and presence of soiling, degradation products, wear and other signs of use. (Garside & Richardson, 2022, p. 9)

The quote summarises quite well the means of what and how, highlighting the extent to which heritage science methods can contribute to research on the past and the future preservation of the objects.

6.1 Visual analysis

The use of visual methods to analyse textiles is comprehensively explained in object-study models (section 2.2). It includes observing all the physical properties of an artefact, and in the case of archaeological samples, of the fragment. The observations are made from the macro to the micro level. In my definition of the process, we move from the macro to the micro level when additional equipment is needed to aid with the visual analysis. Visually distinct materials and possible ornamentations and fasting solutions are recorded based on analysis of a piece of clothing or a whole textile, as well as measurements of the size, shape, pattern and structure, and locations of the seams. Also, any possible signs of alteration or wear and damage are traced at this step in the process.

Micro-level observations take into account smaller patches and fragments as well, and the weave pattern and thread count are observed. Plying and the twist of the yarns are essential components of the analysis. Often, observation at this level is most feasible under a stereo microscope (Emery, 1994; Gillis & Nosch, 2007; Walton Rogers & Eastwood, 1988).

6.2 Textile samples and their relevance

For material identification, a small sample is required. It should be as small as possible. Cultural heritage objects, especially archaeological fragments, should be left as intact as possible for future researchers and the development of more advanced and non-destructive methods. Sample quantity requirements can be downsized with the use of helpful devices. For example, a portable Dino-Lite microscope, which can be connected via a USB port to a laptop, provides an *in situ* possibility to measure yarn thickness and the twist of the yarn, meaning that only a minimal sample size requires a microscope.

When studying woven textiles, a sample of both the warp and weft should be analysed because it is possible, and quite common, that they are of different yarn types and possibly even materials. Yet, this is not always possible due to the excessive number of samples being studied, the condition of the textile or the lack of a prospective sampling spot.

The sample removed from the textile should always be taken in as imperceptible a manner as possible. Holes, unravelled yarns or seam allowances should be taken advantage of when collecting a sample. It has happened on occasion that the textile is too perfectly made to allow for a sample to be taken. For the microscopy analyses done as part of this research project, 2 mm of yarn has been more than enough. For storing the samples, I have used Eppendorf tubes. I always aim to save some of the sample to store in the archive for future research.

Fibre identification methods are continuously being developed and refined to be non-invasive and non-destructive processes.

6.3 Microscopical observations

6.3.1 Sample preparation

Samples are studied and prepared using a stereo microscope. I use a petri dish for the surface — a microscopy glass slide fits easily in the petri dish, leaving plenty of room to operate on the sample at the side of it. With the aid of two tweezers, I divide

the sample on the glass slide, mounting it for cross-cuttings and setting aside some pieces to store for future use. Notes on colour, condition and appearance are made. When making permanent mountings of the fibers on the glass slide, I use Entellan™ new (Merck KGaA, Darmstadt, Germany) permanent mounting media, while several options exist for preparing cross-cuttings, all of which are thoroughly explained in **Paper V**. Entellan™ new has a similar reflective index (RI 1.49–1.50) as liquid paraffin, which is recommended for textile fibre observation (Greaves & Saville, 1995, p. 7). Sample preparation must be done in a well-ventilated laboratory space due to the fact that Entellan™ new contains xylem, which is unhealthy to breath. Drying of the glass slides should be done in a fume hood. If many samples are prepared in a row, between each sample equipment (e.g. tweezers, surgeon's knife, petri dish) should be carefully cleaned with isopropanol to avoid contamination. Also, using a face mask is mandatory so as not to lose samples by accidentally sneezing or snorting or otherwise creating a disturbance in the air flow.

6.3.2 Longitudinal characteristics

Longitudinal characteristics of the fibres are studied using a transmitted light microscope (TLM) and polarized light microscope (PLM). Or to be exact, TLM and PLM are the same type of microscope, but some light-directing filters are added to the TLM when using polarised light. I use objectives of 5x, 10x 20x and 40x magnification. Morphological details of cross markings, dislocations, convolutions and fibrillation are studied under the TLM. Signs of microbial activity or other degradation processes are detected at this stage. The whole area under the coverslip is studied systematically (Greaves & Saville, 1995, p. 25). PLM enhances the visibility of the cross markings and dislocations, and the black background is less tiring for the eyes when making observations. Hence, PLM is highly recommended when studying bast fibres.

6.3.3 Modified Herzog test

Based on the birefringence properties of bast fibres, their twist direction can be determined by using the modified Herzog test with a full wave-length plate (lambda plate) and PLM. This method has been thoroughly discussed by Haugan and Holst (2013). The challenges encountered when using this method are discussed in section 8.3.3 and **Papers I** and **IV**. Flax and nettle have an S-twist in the microfibrils at the S2 layer, whereas hemp has a Z-twist (Bergfjord & Holst, 2010).

6.3.4 Cross sections

Plant fibres are hollow, and they all have a species-specific morphological appearance. Challenges emerge because the differences in fibre shape as well as lumen size and shape tend to vary based on the growing conditions. Assumptions should thus not be made based on a single fibre; rather, a group of fibres should be examined in a holistic manner. Methods for conducting cross-cuttings are explained in **Paper V**. In general, flax has a polygonal shape with a narrow lumen, while hemp has a more or less polygonal shape with a wider lumen (Catling & Grayson, 1982). Nettle has a more kidney-shaped outline and lumen is long and flat (Lanzilao et al., 2016). Cotton can resemble nettle in its shape, but when not fully matured it is more bent and closer to a C-shape in appearance (Moulherat et al., 2002; **Paper III**).

6.3.5 Calcium oxalate crystals

Bast fibre plants produce calcium oxalate crystals in fibre-surrounding tissues and their presence can be used as one identification parameter. Hemp and nettle produce cluster crystals, while hemp also produces solitary crystals. With flax, no appearance of calcium oxalate crystals has been reported to date by researchers (Bergfjord & Holst, 2010). Due to their morphological location, it is possible and probable that due to the processing of the fibres, or in the case of archaeological finds the soil conditions, these crystals may have vanished (Bergfjord & Holst, 2010; Lukešová et al., 2017; Paper I).

Calcium oxalate crystals can be detected with PLM or plasma ashing and by observing the burned sample with SEM (Bergfjord & Holst, 2010; K. Jakes & Mitchell, 1996). Only a few samples studied for the purposes of this thesis have revealed the presence of such crystals when using PLM, so it is clear that flax identification should not be based on this method. Hence, the presence of calcium oxalate crystals verifies the fact that a fibre sample is not flax, but their absence is not a straightforward indication of it being flax. As a method, plasma ashing destroys the samples, meaning it cannot be recommended from the contemporary viewpoint of preserving heritage materials. Instead, non-invasive methods should be preferred for the study of heritage materials, such as Wide-Angle X-ray Scattering (WAXS) (Viljanen et al., 2022).

6.4 X-ray diffraction studies with WAXS

X-ray diffraction and scattering studies make it possible to observe materials that have crystalline structures, such as plant fibres with cellulose, which is a crystalline structure. The amount of relative crystallinity can be measured, as can the size and

orientation of the cellulose crystals. The method could potentially be used to identify plant fibres (Müller et al., 2004, 2006; Viljanen et al., 2022). The major advantage of using WAXS equipment instead of synchrotron for diffraction studies is its low cost and availability.

As mentioned in the previous section, calcium oxalate crystals can be detected with this method. WAXS provides the possibility to study crystallite structures in a non-invasive manner. It also detects damaged and partial crystals. Another possible solution for diffraction methods is to study the degradation of plant fibres. Measurements of relative crystallinity could be used to determine the type and state of decay of heritage textiles (Müller et al., 2007; Viljanen et al., 2022).

In **Paper III**, WAXS equipment was used to obtain crystal-level knowledge of cotton fibres and to test whether the method can detect differences in cotton species that are otherwise remarkably similar. Heritage samples were prepared for analysis by placing them between two Mylar foils that were secured to a metal washer with double-sided tape. The samples remained intact, making it possible to still conduct TLM/PLM and cross-sectional analyses using the same samples.

6.5 Computed Tomography methods

Computed Tomography is widely used in medical research and additionally provides a non-invasive way to study the inner structures of textiles or yarn samples or even fibre characteristics (Garside & Richardson, 2022, p. 17; Lipkin et al., 2020). The sample size is dependent on the resolution of the equipment. Hospital situated computed tomography (CT) scanners are meant for human-sized samples, while micro-CT and nano-CT scanners are for much smaller samples. With the aid of x-ray radiation, the sample is imaged at the frequency determined by the resolution. The images are then compiled to form a 3D-presentation that can be studied in various ways. In digital form, the sample can aid in studying both the inner and external structure of textiles.

In **Paper IV**, two Late Iron age samples were imaged using a micro-CT scanner to learn about their use. We wanted to test whether it was possible to detect the species-specific morphological characteristics of the fibres with this method, with the objective being to preserve the integrity of the finds. The samples were imaged in Eppendorf tubes and stabilised with small Mylar-foil balls.

6.6 Fourier-transform infrared spectroscopy

As explained in section 2.4.3, bast and plant fibres are difficult to distinguish between when using FTIR due to their similarities in chemical composition. Nevertheless, in **Paper III** FTIR was used to verify the identification process. In undegummed silk, the two filaments stay together and can share a similar

appearance with cotton. Silk, being a protein fibre, has a clearly distinctive spectrum observable with FTIR as opposed to cellulose fibres.

7 Results

In this study, the research questions overlap and each is discussed in at least two papers (Table 2).

Table 2 Discussed research questions in every paper and dating of the material

Research question / research themes	**Paper I**	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Feasibility of three-stage bast fibre identification procedure	X	X		X	
Feasibility of novel scientific methods in fibre identification			X	X	X
Cultural history	X	X	X	X	
Terminology	X	X	X	X	
Modern	X		X		X
Ethnographic		X	X		
Archaeological			X	X	

7.1 Paper I: Three-stage identification procedure for bast fibres

Paper I, 'Seeking Nettle Textiles – Utilizing a Combination of Microscopic Methods for Fibre Identification', set the stage for the entire thesis. The main aim and the discussion of the results focus on a three-stage procedure for separately identifying flax, nettle and hemp. In **Paper I,** the procedure was tested on a sample of museum textiles from the National Museum of Finland that were presumably made of nettle. The paper problematised the terminology dealing with bast fibres and linen textiles, which was continued in **Papers II, III** and **IV**. The results confirmed that nettle was used in Obi-Ugrian offering cloths, in a White Karelian shirt and in an intricately designed apron from the 18th century. The paper proposed definitions for cross markings and dislocations, terminological aspects that had not

yet been clearly delineated in the existing literature. It also introduces a discussion regarding the need for greater openness and transparency in identification methods as well as the importance of utilising a heritage science approach for the study of modern object studies.

7.2 Paper II: White Karelian textile tradition

Paper II, 'Examining the White Karelian Textile Tradition of the Late Nineteenth Century—Focus on Plant Fibres', provides a material identification of 41 plant fibre textiles. Flax, nettle, hemp and, most extensively, cotton were all discovered in the samples. The objects were also analysed by structural, material and cultural means from an object study standpoint. *Rätsinäs*, *sorokkas*, together with varying headgear, *käspaikkas* and burial socks were addressed closely. The paper likewise discusses textile terminology, textile culture and manufacturing as well as the fibre properties of historical cotton.

7.3 Paper III: Research methods for heritage cotton fibres

Paper III, 'Research methods for heritage cotton fibres – case studies from archaeological and historical finds in a Finnish context'**,** was inspired by the questions concerning the characteristics of heritage cotton fibre that emerged in **Paper II**. Fibres from all four commercially cultivated cotton species (*G. arboretum*, *G. barbadense*, *G. herbaceum* and *G. hirsutum*) were obtained from modern seeds and studied to determine if any species-specific characteristics could be identified in them. This was the first time that morphological differences were studied in such detail. They were observed longitudinally using TLM and SEM. Based on the cross-sections, their diameters were measured and their maturity was observed. In addition, WAXS was used to measure their ultrastructural parameters, such as crystal width, relative crystallinity and crystallite orientation.

All the resulting data was compared with results from recently identified archaeological cotton samples from Finland (14th to 17th centuries), as well as a selection of White Karelian cotton samples analysed in **Paper II**, to determine what cotton species might have been utilised when manufacturing these textiles. FTIR and micro-CT were used to validate the identifications, revealing that the samples were indeed cotton. Through an extensive literature review of cotton's cultural origins around the world and our own results, we were able to draw some conclusions about the material.

7.4 Paper IV: Late Iron Age bast fibre materials

Paper IV contains updated arrival dating for flax and hemp in Finland based on the existing archaeobotanical literature. It also discusses recent developments in identification methods for bast fibres. Previous archaeological plant fibre finds from Finland and their identifications are summarised in the introduction.

The results focus on the identification and structural analysis of seven textile samples using TLM. The three-stage procedure appeared suitable for archaeological fibres. All the yarns were single-plied and Z-twisted, while the sole weaving structure was plain/tabby. This is in line with previous Fenno-Scandinavian finds. Even though it was possible to image the cross-section of a flax fibre with Micro-CT, it was not suitable for identification purposes due to poor resolution. Hence, it is better suited for studying yarn and weaving structures. Likewise, WAXS failed to identify the flax fibre sample, but it could be utilised, for example, to observe a plant fibre's degradation stage.

7.5 Paper V: Cross-sectioning textile fibres

Paper V, 'My experiments with cross-sectioning textile fibres'**,** is a purely technical account of different cross-cutting techniques suitable for heritage fibres. **Paper I** explains how I use the cross-sectional fibre morphology as one of the parameters in identifying bast fibres. Additionally, cross-cuttings are called into question when, for example, the pigment cells in protein fibres or the maturity of cotton are the subjects of study.

When operating with reference fibres that are abundantly available, cross-cuttings can easily be produced using a metal-plate technique. But what comes to heritage fibre samples, they require much more delicate measures. The existing literature does not give straightforward advice for how best to use such techniques, especially if quality images for publications are needed. During my doctoral work, I experimented with and improved various cutting techniques. **Paper V** summarises these experiences for the good of the research community.

8 Discussion

8.1 Bast fibres

Paper I presents a table of mutually exclusive characteristics, whereas an improved version of it (Table 3) is presented below. The process of successfully separately identifying bast fibres requires multiple methods and recognition targets. The microfibrillar orientation of bast fibres is analysed with the modified Herzog test, with their cross-sectional shape and lumen size observed from the cross cuttings, while the possible presence of calcium oxalate crystals can be detected with polarized light or x-ray diffraction studies (Viljanen et al., 2022).

Table 3 Mutually exclusive characteristics of flax, hemp and nettle fibres

	Flax	Hemp	Nettle
Microfibrillar orientation	S	Z	S
Cross-sectional shape of a single fibre	Polygonal	Polygonal	Oval
Lumen	Small	Wide	Flattened
Calcium oxalate crystals	No	Yes	Yes

8.2 Textiles and terminology

Terminology issues are addressed in **Papers I, II, III** and **IV**. The term *'liina'* in the Finnish context, *'linen'* in an English context, have caused much confusion and inaccuracy in bast fibre textile research due to its context relations. *'Liina/linen'* has been used as a general term for plant fibre bedsheets and towels, sometimes as a general term for textiles made of flax or hemp, and in Finland, depending on the geographical location, as either flax or hemp (Dolan, 2016, p. 55; Kaukonen, 1946; Skoglund, 2021). According to Manninen (1922, p. 108), the confusing use of the term *'liina/linen'* in Finland arises from the times when hemp became the more preferred crop in eastern Finland, with the term '*liina*' inherited from flax then transferred to hemp. If it is not confusing enough that *'liina'* means flax in western Finland and hemp in eastern Finland, Kaukonen (1946, p. 109) provides us with

one more confusing terminological detail. In eastern Finland, sometimes *'liina'* is only used to refer to the female hemp plants, while male plants are called *'koiras'*.

Decline in the use of hemp as a textile fibre in Finland occurred already before the 20th century, with flax thus gradually becoming a synonym for the term *'liina'* in spoken language. In English, the word flax is used when the plant is still growing and '*linen*' when found in textile form. This discrepancy has created distortions in heritage material displays in museums, where the general assumption for a long time had been that all bast fibre textiles should be identified as flax (Skoglund, 2020, p. 67). Already in 1938, *Popular Mechanics* magazine estimated that probably half of all linen imported into the US was actually made of hemp (*Popular Mechanics*, 1938, p. 144A).

Another confusing concept is the term *'nettelduk'* and its variants. Kaukonen (1946, p. 24) already speculated more than half a century ago that the actual material is something other than nettle, probably cotton or flax. This term becomes increasingly common in estate inventory deeds during the 18th century — usually in the context of an apron, a '*näsduk*' (handkerchief) or a '*halsduk*', which most probably has been a sort of detachable collar. All this implies that a '*nettleduk*' was most likely a really fine and light bast fibre fabric — just like the apron studied in **Paper I**. It was clearly identified as nettle, so maybe nettle was not just the name for the fabric. Researchers have also speculated that the material termed *'nettelduk'* could have been Asian-imported ramie (*Boehmeria nivea*), the morphological fibre characteristics of which closely resemble stinging nettle (Platonova, 2018; **Paper I**). This issue certainly requires further study.

8.3 Development of methods

8.3.1 Microscopic examination of fibres' longitudinal characteristics

Vocabulary issues related to dislocations and cross markings are discussed in **Paper I**. Depending on the field, they are referred as, for instance, nodes, kinks, kink-bands, defects, micro-compressions, micro-compressive defects or slip planes (Hernandez-Estrada et al., 2016; Hughes, 2012), commonly without making any attempt at distinguishing between the two types of malformations. Such a distinction is important, however, because cross markings only occurs on the surface of the fibre, whereas dislocations affect the whole structure of the fibre. An otherwise wonderful article by Melelli et al. (2021) states that kink-band areas would have been larger in size and occurred at a greater quantity in ancient flax fibres. In their paper, Figure 3 proceeds to show difference between old and modern flax and how cellulose macrofibrils are disorganised in the kink-band area of old but not new flax fibre, imaged with multiphoton microscopy with second harmonic

generation (SHG). What the authors miss, though, is that the images of new flax fibres are from cross markings at straight parts of the fibres, whereas the images from the old flax fibres are from the dislocations.

Another issue that I disagree with is the statement that the malformations would have been caused by mechanical stress during the extraction process (Hughes, 2012, p. 603; Melelli et al., 2021, p. 1201). Hänninen et al. (2012) argues that the number of malformations increases when the fibres are processed more. While such an occurrence may be possible, it is also possible that the increase is due to the growing conditions and harvesting time. The authors did not state whether or not their research material came from the same field. Additionally, it must be noted that even unprocessed fibres exhibited these types of defects. Thygesen and Asgharipour (2008) experimented with windy and moist growing conditions and came to the conclusion that they had little effect on the frequency of dislocations. The possible effects of soil nutrition levels and harvesting time also require further study.

If bast fibres are observed with TLM, then the cross markings seem like cracks or fractures on the surface, the kinds of defects that one could imagine being caused be mechanical force. But when the fibres are observed with SEM, it is possible to notice that actually the cross markings and dislocations are swollen accumulations on the surface of the fibre (Bergfjord & Holst, 2010; Rast-Eicher, 2016; **Paper I**). My hypothesis is that such accumulations form as a result of pressure from surrounding plant cells (**Paper I**); it is quite difficult to imagine what forces of nature would cause this kind of swelling in the fibres when exposed to mechanical stress and bending while processing. My research material consists of applying highly processed materials to fibres extracted directly without processing from the stem, and these extraction methods have not had any effect on the frequency of malformations in the fibres. The method as well as how growing conditions affect the physical appearance of the fibres both require further study to better understand such phenomena.

The longitudinal characteristics of cotton fibres and the challenges in identifying them are discussed in **Paper II** and **III**. Based on the ideas presented in **Paper II**, it can be stated here that modern cotton fibres have a flat, ribbon-like appearance with irregular convolutions, whereas in older heritage material the characteristics have blurred more with those of other textile fibres. Often, the fibres are not properly flattened due to uneven ripening (Moulherat et al., 2002) and they can share visual similarities with undegummed silk (Kirkinen et al., 2023). The surface can be filled with cross markings, and as a result, identification can be misleading with bast fibres. **Paper III** showed the flat, ribbon-like properties are typical of the *G. hirsutum* species, which is by far the most dominant type of cotton, comprising an approximately 90% share of contemporary markets. When studied with TLM, the above-mentioned confusing properties seemed more common for the *G.*

arboreum and *G. herbaceum* species, which are the ones that historical sources show were common in Europe before *G. hirsutum* captured the markets.

8.3.2 Cross-sectional sample preparation

Throughout the entire doctoral research process, much attention was paid to developing a suitable and functional method for obtaining a cross-cutting of a fibre sample. The most commonly used method, which involves a metal plate (Greaves & Saville, 1995, p. 39), requires fibres in such quantity that it is unsuitable for the study of heritage materials. Given the lack of a suggested microtome (Greaves & Saville, 1995, p. 40), the cross-cuttings studied in **Paper I** were obtained with an Entellan™ new and cork sheet. This method was inspired by a procedure discussed by Goodway (1987, p. 31). With a large quantity of samples, **Paper II** assesses the results of a cross-sectioning experiment with paper glue (Rast-Eicher, 2016, p. 70). **Papers II** and **IV** introduced a cross-cutting method used for TEM samples. With that method, fibres were mounted in an LR White resin (Agar Scientific Ltd, Essex, UK) and sliced with ultramicrotome into 2000 nm slices. All the methods are revisited and thoroughly explained in **Paper V**.

Paper glue and cork sheet methods are fast-forward methods useful when the analysis needs to be time and work efficient. With a little practice, cross-sections can easily be observed in TLM, though imaging with proper pictures is difficult. The ultramicrotome method is again time consuming, yet the images are perfect. A suitable method should be selected based on the requirements. Lately, there has been much discussion in the field as to whether cross-sectioning is an appropriate method for fibre identification at all (Lukesova & Holst, 2021; **Paper IV**). It is important to emphasise that it should never be used as the only identification method. Abnormalities do appear due to natural variations, and that is why analysis should not concentrate on a single fibre; rather, the cross-cuttings should be observed holistically.

8.3.3 Modified Herzog test for determining microfibrillar orientation

Originally already introduced in the 1950s, the Modified Herzog test reveals the direction of the microfibrillar orientation of the fibres. The principle of this method is comprehensively explained by Haugan and Holst (2013). Using PLM and a lambda plate, shades of blue and yellow in the horizontal and vertical directions disclose the orientation of the fibre sample. The problem is that the results reveal only the S-twist or Z-twist direction, and this is not enough for identification. For example, flax and nettle have an S-twist, whereas hemp and jute have a Z-twist. The

Modified Herzog test is an irreplaceable tool in identification, but it is feasible only as one of the methodological components in the procedure.

Paper I and **IV** discuss problems related to the Modified Herzog test. When using a Leica 4500P microscope, which has been the primary tool in this study, the lambda plate can be slid between a 135° angle and a 225° angle. In the middle, at a 180° angle, it has no effect on the view, but depending on which side of the adjusted 45° angle the lambda plate is on, the marker colours of blue and yellow are reversed (Figure 7). The ISO standard 20706–1:2019 (International Organization for Standardization, 2019) for this method does not take this effect into account at all, despite the opposite appearance of the results in terms of colour. Explaining this physical phenomenon is beyond the scope of this study. Thus, it is highly recommendable to test the equipment with known reference fibres before interpreting the results. Even more importantly, the potential problems in interpreting the results makes the images in prior publications incomparable and the colour changes should only be compared within that particular study.

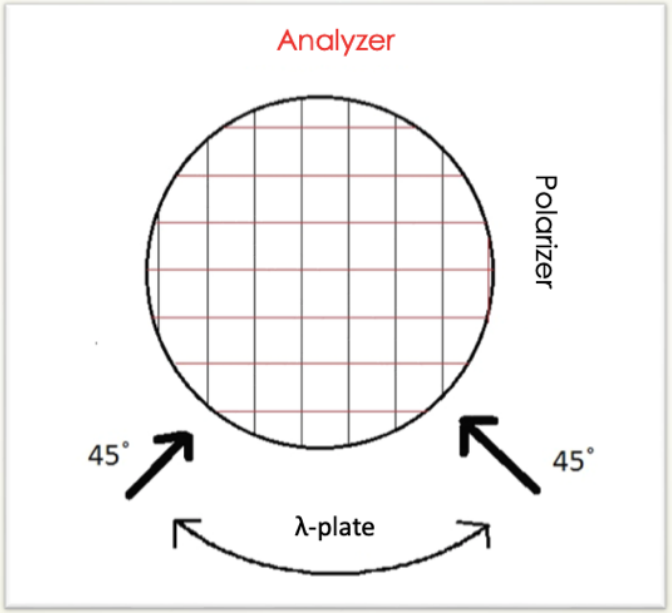

Figure 7 Diagram showing the application of a lambda plate with a Leica 4500P microscope.

8.3.4 WAXS for measuring cellulose crystals

In **Paper III**, WAXS was utilised to measure cellulose crystals from reference samples as well as the White Karelian cotton fibres samples discussed in **Paper II**. Some plausible similarities in the azimuthal intensity of the reference sample and heritage samples were detected, but this would require further study with a much

larger number of samples. The same trend already noted by Viljanen et al. (2022) in relation to bast fibres was apparent in the cotton fibre samples. For a reason that we could not explain, all the heritage samples have systematically larger cellulose crystallite sizes.

WAXS has its applications in cellulose-based plant fibre studies, as explained in section 6.4, but it is unfeasible as a sound identification tool for heritage fibres. Compared to the expensive and inaccessible particle accelerator-based synchrotron method, the WAXS method, where radiation is formed via an X-ray tube, is a low-cost and easily available alternative for studying crystal structures in plant fibres.

8.3.5 Micro-CT for 3D-analysis of textile structures

The resolution level with micro-CT imaging was not accurate enough to detect any of the morphological characteristics in bast fibres required for identification. Still, the method proved advantageous for studying degraded archaeological textile finds, the structure of which would otherwise be unobservable. Samples in this study consisted of simple tabby woven fragments, but in the case of, for example, complicated tablet-woven bands in a pseudomorph state, it can be a valuable aid in research.

Whereas micro-CT resolution was insufficient for fibre studies, nano-CT has a suitable resolution level for such studies (Kuan et al., 2020). It can be assumed that in the future, this equipment will become more extensively available for heritage science purposes.

8.3.6 Degradation processes

There are multiple chemistry-based processes that affect the deterioration of plant fibres — primarily caused by oxidation, acid or alkaline hydrolysis. The observations that I have made about the types of degradation affecting plant fibres can probably be explained by the influence of relative humidity (RH) and the previously mentioned processes. When the RH is less than 30%, desiccation can occur, causing the fibres to shrink and become brittle. Acid hydrolysis can be observed as a mechanical weakness and lack of flexibility. Cellulose structures, again, tolerate alkaline hydrolysis much better (Garside, 2022, pp. 341–342). According to Garside and Wyeth (2006), hydrolysis causes scission and a breakage of the cellulose polymers. Biological degradation caused by pests, moulds and microbes is one possible treatment for plant fibres, especially when humidity and temperature conditions are favourable (Garside, 2022, p. 342).

After analysing a relatively large number of samples, also beyond the scope of this thesis, it has been possible to comment on the visual markers of degradation process types at the fibre level. Even though numerous studies on textile

conservation explain the deterioration processes at the chemical level (Hearle et al. 1998, 379; Garside & Wyeth 2006, 67-68), it has been difficult to find information on how they appear visually in the fibres. The input of this research was to study and present the visual changes in fibres, that most probably manifest chemical changes that occurred at a molecular level. The detected degradation modes are explained here visually.

I found polarised light feature when using a microscope quite useful for observing the fibres. When the degradation process has reached a certain peak, the morphological features of the bast fibres become difficult to detect. Hence, the dislocations and cross markings seem invisible. Polarised light emphasises these features and improves the possibility for observing them.

Degradation processes appeared in plant fibres in several manners. The following processes were detected in the analysed samples:

1) Some sort of foreign matter had become stratified on the surface of the fibres,
2) the physical structure of the fibres had eroded to form small holes,
3) the fibres have started to dry and form a pseudomorph,
4) in contrast to this process, some fibres samples had started decaying via some undefined wet process,
5) yarn-like unravelling, fibrillation, of the structure was also detected.

Contamination, which can be the result of dirt, soil or a colony of micro-organisms on the surfaces of the fibres, hindered the possibility to identify and analyse the fibres (Figure 8). The constituent nonetheless affected the visual appearance of the fibres, and in the case of micro-organisms, they undoubtedly degraded the fibres by positioning them as the nutriment.

Figure 8 Some foreign matter stratified on the surface of the fibres (Ravattula H2:5921).

Figure 9 Small holes on the surface of the fibre (SU4522:90b).

Often when the contamination was detected, small holes had formed on the surface of the fibres due to erosion (Figure 9). The holes have been caused by the micro-organisms, fungi and bacteria present on the fibre. According to Hearle, Lomas and Cooke (1998, pp. 378–379), especially *Fusarium oxyporum* (which is a white-coloured *ascomycete* fungus), *Sporotrichum pruinosum* (which is specialised in decomposing lignin) and *Penicillium funicolosum* (produces a greenish or bluish mould) are particular to cellulose and commonly found in soil. It is also possible that the holes were generated by acidic conditions in the environment. Bast fibres are sensitive to accelerated degradation in acidic conditions, which causes acid-catalysed hydrolysis, and in the end the total dissolution of the bast fibres (Hearle et al., 1998, p. 379).

Based on the samples, it was possible to detect two types of decaying – I refer to them as wet and dry modes. In the dry mode, the fibres became brittle and difficult to handle (Figure 10). The fibres did not unravel from the yarn; they were stuck together, and elasticity was lost. Such samples, with even the most careful sample preparation, will likely crumble into dust. Hearle, Lomas and Cooke (1998, p. 391) have detected a type of oxidation that occurs when the textile comes into contact with the body fluids. As a result, the fibres become extremely brittle, but the morphological structures can still be observed. Supposedly, this will be the case in at least some samples. Boersma (2007) states that brittleness is caused by cross-linking in the polymer chains.

With the wet degradation mode, the fibres broke apart like a rotted tree or tender meat (Figure 11). Often some elasticity was left, but the samples broke apart in small, longitudinal pieces. In comparison to the dry mode, where the material shrunk together, in the wet mode all the material tended to fragment into shivers. All the typical morphological features, cross markings and dislocation appeared in diluted form, and they were only visible with polarised light. All this can be explained by Jakes's (2000, p. 65) notion that low crystallinity fibres are soft and weak.

Sometimes the yarn had formed a stone-like lump, which was interpreted as a (preliminary) pseudomorph. When the yarn begins to transform into a pseudomorph, the original elements are replaced with minerals and other elements and only the original structure remains (Gleba & Mannering, 2012).

A surprising phenomenon appeared in several samples. The microfibrils of fibre had begun to unravel in the same way as strands unravel from a yarn (Figure 12). Bast fibres consist of microfibrils that form a similar structure as in, for example, water hoses — crossing layers of fibres, or in this case, fibrils. The lignin and hemicelluloses, which function as glue in the bast fibre, had decomposed, and the highly crystallised cellulose structure had remained and fibrillated. Usually this process is caused by wear and washing (Hearle et al., 1998).

Figure 10 Degradation in the dry mode (Ravattula H20:17).

Figure 11 Degradation in the wet mode (Köyliö 312.3B).

Figure 12 Fibrillation in the nettle fibre (SU4522:92a).

Figure 13 Mould spores on the cotton fibre from the tying ribbon of *otsipanta* (SU4522:81).

8.4 Practical applications for heritage science

To best demonstrate the practical applications of the findings presented in this thesis, an example is needed. In addition to material identification, micro-level observations of objects give valuable information about their condition. For example, the girl's headband, *otsipanta* (SU4522:81), which was studied in **Paper II**, seemed to be in good condition at first glance. Yet, the microscopic examination of it revealed the tying ribbons of the *otsipanta* to be under severe microbial attack by moulds (Figure 13). Without close examination, I would not have noticed the condition of the textile, which required conservation treatment.

9 Conclusions

In this doctoral thesis, I have presented a procedure to identify flax, hemp and nettle by combining several methods. I have tested the three-stage procedure with modern reference fibres and different heritage materials with a long time span and under differing conditions, which enhanced the reliability of the results. In addition to bast fibres, cotton ended up playing a notable role in this study. Distinctive characteristics of all four commercially cultivated cotton species were detected with multiple methods. In the beginning of my work, I had high expectations for finding a measurement tool that provides numerical data in an objective manner, thus ensuring the reliable identification of fibre material. The search, though, for a quantitative measurement-based method will continue beyond the confines of this study.

From object studies point of view, I was able to take the analysis to another level by including micro-level knowledge gained with microscopy methods in the study of cultural history. By applying heritage science methods to the research material, I was able to reveal hidden knowledge about the textiles. I gave voice to the White Karelian textiles and illustrated the early history of cotton in Finland. Also, a potential use context for the Ravattula, Ristimäki finds was discussed.

The most significant change what has happened in historical textile research while I was conducting my research has been the requirement for greater openness in research methods, and I am glad that I have been able to contribute to that shift towards transparency. The cumulative nature of science cannot occur if research is not reproducible. When it comes to terminology concerning bast fibres, and especially the confusing term linen, greater awareness within research community has occurred through open discussion. Instead of broad general terms, plant-specific names are now preferred.

At the moment, few researchers are performing identification analyses due to its subjective and complicated nature. It would be desirable for such methods to become more applicable at a general level. The techniques are not part of any university programme and can only rarely be studied in organised courses. More co-operation among researchers working with heritage textiles is needed to further develop reliable tools for identification. One good example of a much needed network programme is the pan-European COST Action CA 19131 Europe through

Textiles: Network for an integrated and interdisciplinary Humanities — Euroweb programme. Similar initiatives could be implemented at the national level, too.

Another concrete advancement for the heritage field would be some sort of nationally administered archive for the samples taken from heritage textiles. In an effort to minimise the destruction of valuable heritage textiles, all the excess samples, permanently mounted microscopy slides and epoxy/resin blocks could be stored collectively with detailed information for future use. It is pointless for every researcher to take new samples when previous samples could be utilised as well. Valuable heritage samples are accumulating into every researcher's cupboard. Currently, the ethics in sample taking and in conducting research on heritage textiles, both which have been discussed throughout this thesis, are topical issues in the field.

References

Aalto, M. (1982). Archaeobotanical studies at Katajamäki, Isokylä, Salo, South-West Finland. In *Pact*, *7*(1), 137–147. Council of Europe.

Aikasalo, P. (2006). Hiljainen museo esine puhuu—Ajatuksia ja tutkimuskysymyksiä museoesineiden äärellä. In L. Kaukinen & M. Collanus (Eds.) *Tekstejä ja kangastuksia—Puheenvuoroja käsityöstä ja sen tulevaisuudesta*. Akatiimi.

Arponen, A. (2015). The Medieval Skull Relic of Turku Cathedral. *Mirator*, *2015*(1), 104–116.

Arponen, A., Vanden Berghe, I., & Kinnunen, J. (2018). Red fabrics in the relic assemblage of Turku Cathedral. *Relics@ the lab–An analytical approach to the study of relics. Interdisciplinary Studies in Ancient Culture and Religion, 20*, 3–20. https://doi.org/10.2307/j.ctv1q26xmd

Aspelin, E. (1879). Keskiaikainen ompeluteos. In *Suomen muinaismuisto-yhtiön aikakauskirja,4,* 177–179. Suomen muinaismuisto-yhtiö.

Bergfjord, C., & Holst, B. (2010). A procedure for identifying textile bast fibres using microscopy: Flax, nettle/ramie, hemp and jute. *Ultramicroscopy*, *110*(9), 1192–1197. https://doi.org/10.1016/j.ultramic.2010.04.014

Bergfjord, C., Mannering, U., Frei, K. M., Gleba, M., Scharff, A. B., Skals, I., Heinemeier, J., Nosch, M.-L., & Holst, B. (2012). Nettle as a distinct Bronze Age textile plant. *Scientific Reports*, *2*(1), Article 1. https://doi.org/10.1038/srep00664

Boersma, F. (2007). *Unravelling textiles: A handbook for the preservation of textile collections*. Archetype.

Caple, C. (2006). *Objects: Reluctant witnesses to the past*. Routledge.

Catling, D., & Grayson, J. (1982). *Identification of vegetable fibres*. Chapman & Hall.

Cosentino, A. (2016). Terahertz and Cultural Heritage Science: Examination of Art and Archaeology. *Technologies*, *4*(1), Article 1. https://doi.org/10.3390/technologies4010006

Dolan, A. C. (2016). *The Fabric of Life: Linen and Life Cycle in England, 1678-1810*.

Dunsmore, S. (1993). *Nepalese textiles*. British Museum Press.

Edwards, H. G. M., & Wyeth, P. (2005). Case study: Ancient Textile Fibres. In H. G. M. Edwards & J. M. Chalmers (Eds.), *Raman spectroscopy in archaeology and art history* (pp. 304–324). Royal Society of Chemistry.

Emery, I. (1994). *The primary structures of fabrics: An illustrated classification*. Thames and Hudson.

Fernström, P. (2012). *Damastin traditio ja innovaatio: Tekstiilitaiteilija Dora Jungin toiminta ja damastien erityisyys*. University of Helsinki.

Fernström, P. (2018). *Pellavaliina: Tampellan damasti 1859-1977*. Maahenki.

Fleming, E. M. (1974). Artifact Study: A Proposed Model. *Winterthur Portfolio*, *9*, 153–173.

Garside, P. (2022). Textiles. In P. Garside & E. Richardson (Eds.), *Conservation science: Heritage materials* (2nd edition, pp. 331–387). Royal Society of Chemistry.

Garside, P., & Richardson, E. (2022). Analytical Techniques in Conservation Science. In P. Garside & E. Richardson (Eds.), *Conservation science: Heritage materials* (2nd edition, pp. 9–52). Royal Society of Chemistry.

Garside, P., & Wyeth, P. (2003). Identification of Cellulosic Fibres by FTIR Spectroscopy—Thread and Single Fibre Analysis by Attenuated Total Reflectance. *Studies in Conservation*, *48*(4), 269–275. https://doi.org/10.1179/sic.2003.48.4.269

Garside, P., & Wyeth, P. (2006). Textiles. In B. D. Barker, P. Wyeth, H. Roemich, K. Petersen, D. J. Gregory, Y. R. Shashoua, H. Matthiesen, A. E. Charola, E. May, & M. Jones (Eds.), *Conservation Science: Heritage Materials* (pp. 56–91). Royal Society of Chemistry.

Geijer, A. (1979). *A history of textile art: A selective account*. Sotheby Parke Bernet.

Gillis, C., & Nosch, M.-L. B. (Eds.). (2007). *First aid for the excavation of archaeological textiles*. Danish National Research Foundation's Centre for Textile Research; Oxbow Books.

Gleba, M., & Mannering, U. (2012). Introduction: Textile Preservation, Analysis and Technology. In M. Gleba & U. Mannering (Eds.), *Textiles and textile production in Europe from prehistory to AD 400*. Oxbow Books.

Goodway, M. (1987). Fiber Identification in Practice. *Journal of the American Institute for Conservation*, *26*(1), 18.

Greaves, P. H., & Saville, B. P. (1995). *Microscopy of textile fibres*. Bios Scientific.

Gulati, A. N., & Turner, A. J. (1929). A note on the early history of cotton. *Journal of the Textile Institute Transactions*, *20*(1), T1–T9. https://doi.org/10.1080/19447022908661470

Hald, M. (1942). The Nettle as a Culture Plant. *Folkliv*, *1942*(6), 28–49.

Hänninen, T., Thygesen, A., Mehmood, S., Madsen, B., & Hughes, M. (2012). Mechanical processing of bast fibres: The occurrence of damage and its effect on fibre structure. *Industrial Crops and Products*, *39*, 7–11. https://doi.org/10.1016/j.indcrop.2012.01.025

Hardy, K. (2008). Prehistoric string theory. How twisted fibres helped to shape the world. *Antiquity*, *82*. https://doi.org/10.1017/S0003598X00096794

Harlin, E.-K. (2019). Sámi Archaeology and the Fear of Political Involvement: Finnish Archaeologists' Perspectives on Ethnicity and the Repatriation of Sámi Cultural Heritage. *Archaeologies*, *15*(2), 254–284. https://doi.org/10.1007/s11759-019-09366-7

Harvey, K. (2017). *History and Material Culture: A Student's Guide to Approaching Alternative Sources*. (2nd ed.). Routledge.

Haugan, E., & Holst, B. (2013). Determining the fibrillar orientation of bast fibres with polarized light microscopy: The modified Herzog test (red plate test) explained. *Journal of Microscopy*, *252*(2), 159–168. https://doi.org/10.1111/jmi.12079

Hearle, J. W. S., Cooke, W. D., & Lomas, B. (1998). *Atlas of fibre fracture and damage to textiles* (2nd ed.). CRC Press.

Hernandez-Estrada, A., Gusovius, H.-J., Müssig, J., & Hughes, M. (2016). Assessing the susceptibility of hemp fibre to the formation of dislocations during processing. *Industrial Crops and Products*, *85*, 382–388. https://doi.org/10.1016/j.indcrop.2016.01.006

House of Lords Science and Technology Select Committee. (2006). *Enquiry Report on Science and Heritage. HL 256*. Stationery Office. https://publications.parliament.uk/pa/ld200506/ldselect/ldsctech/256/256.pdf

Hughes, M. (2012). Defects in natural fibres: Their origin, characteristics and implications for natural fibre-reinforced composites. *Journal of Materials Science*, *47*(2), 599–609. https://doi.org/10.1007/s10853-011-6025-3

Hukkinen, S. (1991). *Hyötykasvi nokkonen*. Dataliina.

Inha, I. K. (1911). *Kalevalan laulumailta: Elias Lönnrotin poluilla Vienan Karjalassa : kuvaus Vienan Karjalan maasta, kansasta, siellä tapahtuneesta runonkeruusta ja runoista itsestään*. Kansanvalistusseura.

Jakes, K. A. (2000). Microanalytical methods for studying prehistoric textile fibers. In P. B. Drooker & L. D. Webster, *Beyond cloth and cordage: Archaeological textile research in the Americas*. University of Utah Press.

Jakes, K., & Mitchell, J. (1996). Cold Plasma Ashing Preparation of Plant Phytoliths and their Examination with Scanning Electron Microscopy and Energy Dispersive Analysis of X-rays. *Journal of Archaeological Science*, *23*(1), 149–156. https://doi.org/10.1006/jasc.1996.0012

Kaipainen, M. (2017). Sibeliuksen puvut ja pukeutuminen. *Artefactum*, *8*.

Karg, S. (2011). New research on the cultural history of the useful plant Linum usitatissimum L. (flax), a resource for food and textiles for 8,000 years. *Vegetation History and Archaeobotany*, *20*(6), 507–508. https://doi.org/10.1007/s00334-011-0326-y

Karttila, M. (2014). The Cap of St Birgitta of Sweden: Research and conservation of medieval reliquary. In *Textiles: Multidisclipinary Approaches*, *Masf 3*. The Archaeological Society of Finland.

Kaukonen, T.-I. (1946). *Pellavan ja hampun viljely ja muokkaus Suomessa: Kansatieteellinen tutkimus*. Suomen muinaismuistoyhdistys.

Kennedy, C. J. (2015). The role of heritage science in conservation philosophy and practice. *The Historic Environment: Policy & Practice, 6*(3), 214-228.

Kirkinen, T., Wright, K., Suomela, J., & Ilves, K. (2023). Microscopic fibres in soils – The accumulation of textile fibres and animal hairs at the 6th–11th-century CE Kvarnbo Hall settlement site on the Åland Islands, Finland. *Journal of Archaeological Science: Reports*, *47*, 103809. https://doi.org/10.1016/j.jasrep.2022.103809

Kokko, S., Almevik, G., Bentz Høgseth, H. C., & Seitamaa-Hakkarainen, P. (2020). Mapping the methodologies of the craft sciences in Finland, Sweden and Norway. *Craft Research, 11*(2), 177-209.

Korkeakoski-Väisänen, K. (1993). On the Construction of Corded Ware and Decoration. *Karhunhammas*, *15*, 15–24.

Koskennurmi-Sivonen, R. (1998). *Creating a unique dress: A study of Riitta Immonen's creations in the Finnish fashion house tradition*. Akatiimi.

Kuan, A. T., Phelps, J. S., Thomas, L. A., Nguyen, T. M., Han, J., Chen, C.-L., Azevedo, A. W., Tuthill, J. C., Funke, J., Cloetens, P., Pacureanu, A., & Lee, W.-C. A. (2020). Dense neuronal reconstruction through X-ray holographic nano-tomography. *Nature Neuroscience*, *23*(12), 1637–1643. https://doi.org/10.1038/s41593-020-0704-9

Kujala, V. (1948). Antrean Korpilahden kivikautisen verkon kuituaines. In *Suomen museo: Vol. (1947-1948)* (pp. 24–27). Suomen Muinaismuistoyhdistys.

Lanzilao, G., Goswami, P., & Blackburn, R. S. (2016). Study of the morphological characteristics and physical properties of Himalayan giant nettle (Girardinia diversifolia L.) fibre in comparison with European nettle (Urtica dioica L.) fibre. *Materials Letters*, *181*, 200–203. https://doi.org/10.1016/j.matlet.2016.06.044

Lehtinen, I. (1999). *Marien mekot: Volgansuomalaisten kansanpukujen muutoksista*. Suomalais-ugrilainen Seura.

Lehtinen, I., & Sihvo, P. (1984). *Rahwaan puku: Näkökulmia Suomen kansallismuseon kansanpukukokoelmiin = Folk costume : a survey of the Finnish National Museum folk costume collection*. Museovirasto.

Lipkin, S., Vajanto, K., Kallio-Seppä, T., Kuokkanen, T., Niinimäki, S., Väre, T., & Bommel, M. R. (2020). Funeral dress and textiles in 17th and 19th century burials in Ostrobothnia, Finland. In K. Grömer & F. Pritchard (Eds.) *Aspects of the Design, Production and Use of Textiles and Clothing from the Bronze Age to the Early Modern Era. NESAT XII. The North European Symposium of Archaeological Textiles 21st – 24th May 2014 in Hallstatt, Austria*. (pp. 209–221). Leidorf.

Lukesova, H., & Holst, B. (2021). Is Cross-Section Shape a Distinct Feature in Plant Fibre Identification? *Archaeometry*, *63*(1), 216–226. https://doi.org/10.1111/arcm.12604

Lukešová, H., Palau, A. S., & Holst, B. (2017). Identifying plant fibre textiles from Norwegian Merovingian Period and Viking Age graves: The Late Iron Age Collection of the University Museum of Bergen. *Journal of Archaeological Science: Reports*, *13*, 281–285. https://doi.org/10.1016/j.jasrep.2017.03.051

Luutonen, M., Koskennurmi-Sivonen, R., Koski, J. T., Raunio, A.-M., Salo-Mattila, K., Seitamaa-Hakkarainen, P., & Syrjäläinen, E. (1999). *Research at the Section of Craft Science and Textiles Teacher Education at the University of Helsinki*. University of Helsinki.

Popular Mechanics (1938). New billion dollar crop. *Popular Mechanics, Feb,* 238–239. Hearst Magazines.

Manninen, I. (1922). *Pohjoisen Karjalan vanhanaikainen talous: Historiallisten lähteiden mukaan*. Suomen historiallinen seura.

Melelli, A., Shah, D. U., Hapsari, G., Cortopassi, R., Durand, S., Arnould, O., Placet, V., Benazeth, D., Beaugrand, J., Jamme, F., & Bourmaud, A. (2021). Lessons on textile history and fibre durability from a 4,000-year-old Egyptian flax yarn. *Nature Plants*, *7*(9), Article 9. https://doi.org/10.1038/s41477-021-00998-8

Mida, I., & Kim, A. (2015). *The dress detective: A practical guide to object-based research in fashion*. Bloomsbury.

Miettinen, A., Sarmaja-Korjonen, K., Sonninen, E., Jungner, H., Lempiäinen, T., Ylikoski, K., Carpelan, C., & Mäkiaho, J.-P. (2008). The palaeoenvironment of the 'Antrea net find. *Iskos, 16*, 71–87.

Moulherat, C., Tengberg, M., Haquet, J.-F., & Mille, B. (2002). First Evidence of Cotton at Neolithic Mehrgarh, Pakistan: Analysis of Mineralized Fibres from a Copper Bead. *Journal of Archaeological Science*, *29*(12), 1393–1401. https://doi.org/10.1006/jasc.2001.0779

Müller, M., Murphy, B., Burghammer, M., Riekel, C., Pantos, E., & Gunneweg, J. (2007). Ageing of native cellulose fibres under archaeological conditions: Textiles from the Dead Sea region studied using synchrotron X-ray microdiffraction. *Applied Physics A*, *89*(4), 877–881. https://doi.org/10.1007/s00339-007-4219-y

Müller, M., Murphy, B., Burghammer, M., Riekel, C., Roberts, M., Papiz, M., Clarke, D., Gunneweg, J., & Pantos, E. (2004). Identification of ancient textile fibres from Khirbet Qumran caves using synchrotron radiation microbeam diffraction. *Spectrochimica Acta Part B: Atomic Spectroscopy*, *59*(10), 1669–1674. https://doi.org/10.1016/j.sab.2004.07.018

Müller, M., Murphy, B., Burghammer, M., Snigireva, I., Riekel, C., Gunneweg, J., & Pantos, E. (2006). Identification of single archaeological textile fibres from the cave of letters using synchrotron radiation microbeam diffraction and microfluorescence. *Applied Physics A*, *83*(2), 183–188. https://doi.org/10.1007/s00339-006-3516-1

Nanetti, A. (2021). Defining Heritage Science: A Consilience Pathway to Treasuring the Complexity of Inheritable Human Experiences through Historical Method, AI, and ML. *Complexity*, *2021*, e4703820. https://doi.org/10.1155/2021/4703820

National Museum of Finland. (2021, February 25). *The Homecoming, opening in October, celebrates the repatriation of Sámi artefacts to the Sámi homeland, Sápmi*. The National Museum of Finland. https://www.kansallismuseo.fi/en/articles/homecoming-celebrates-repatriation-of-sami-artefacts

Nayak, R. K., Padhye, R., & Fergusson, S. (2012). Identification of natural textile fibres. In R. M. Kozłowski (Ed.), *Handbook of Natural Fibres* (Vol. 1, pp. 314–344). Woodhead Publishing. https://doi.org/10.1533/9780857095503.1.314

Nordman, C. A. (1943). Naantalin nunnien käsitöitä: Kirjontaa ja kudoksia luostariajalta. In *Muistojulkaisu Naantalin 500 vuotisjuhlaan elokuun 23. Päivänä 1943* (pp. 165–198). Oy Suomen kirja.

Nylander, E.-K. (2023). *From repatriation to rematriation: Dismantling the attitudes and potentials behind the repatriation of Sámi heritage*. University of Oulu.

Pearce, S. M. (1994). Thinking about things. In S. M. Pearce (Ed.) *Interpreting Objects and Collections* (pp. 125–132). Routledge.

Perry, D. R., Appleyard, H. M., Cartridge, G., Cobb, P. G. W., Coop, G. E., Lomas, B., Ritchie, G. G., Taylor, C., Welch, M. J., & Farnfield, C. A. (1985). *Identification of textile materials* (7th edition). Textile Institute.

Platonova, R. (2018). *Nokkonen kehruukasvina*. Books on Demand.

Prown, J. D. (1982). Mind in Matter: An Introduction to Material Culture Theory and Method. *Winterthur Portfolio*, *17*(1), 1–19.

Pylkkänen, R. (1970). *Barokin pukumuoti Suomessa 1620-1720*. Suomen muinaismuistoyhdistyksen aikakauskirja 71. Weilin + Göös.

Pylkkänen, R. (1974). The Oriental source of wool intarsia and gilt membrane embroidery and their animal symbolism. In *The use and traditions of mediaeval rugs and coverlets in Finland* (pp. 32–40). Suomen muinaismuistoyhdistys.

Räisänen, R. (2014). Experimental research as a method in craft studies. In S. Karppinen, A. Kouhia, & E. Syrjäläinen (Eds.), *Kättä pidempää: Otteita käsityön tutkimuksesta ja käsitteellistämisestä*. University of Helsinki.

Räisänen, R., Parviainen, E., Rissanen, M., & Suonsilta, H. (2017). *Tekstiilien materiaalit*. Finn Lectura.

Rast-Eicher, A. (2016). *Fibres: Microscopy of archaeological textiles and furs*. Archaeolingua.

Ren, G., Zhang, X., Li, Y., Ridout, K., Serrano-Serrano, M. L., Yang, Y., Liu, A., Ravikanth, G., Nawaz, M. A., Mumtaz, A. S., Salamin, N., & Fumagalli, L. (2021). Large-scale whole-genome resequencing unravels the domestication history of Cannabis sativa. *Science Advances*, *7*(29). https://doi.org/10.1126/sciadv.abg2286

Reza, M., Kontturi, E., Jääskeläinen, A.-S., Vuorinen, T., & Ruokolainen, J. (2015). Transmission electron microscopy for wood and fiber analysis – A Review. *BioResources*, *10*(3), 6230–6261. https://doi.org/10.15376/biores.10.3.Reza

Riikonen, J. (2011). White linen: Cloth of luxury. In *Times, Things & Places: 36 Essays for Jussi-Pekka Taavitsainen.* (pp. 198–221). J.-P. Taavitsainen Festschrift Committee.

Rodenstam, S. (1918). *Om lin och nässlor som spånadsämne i Jämtland*. Emil Janssons boktryckeri.

Rogerson, C. (2022). Introduction. In P. Garside & E. Richardson (Eds.), *Conservation science: Heritage materials* (2nd edition). Royal Society of Chemistry.

Ronimus, J. V. (1906). *Novgorodin vatjalaisen viidenneksen verokirja v. 1500 ja Karjalan silloinen asutus*. Suomen historiallinen seura.

Salo-Mattila, K. (2000). *Keisarinnan sermi: Naiskäsityön suhde taiteeseen 1800-luvun loppupuolella*. Helsingin yliopisto, Kotitalous- ja käsityötieteiden laitos.

Salo-Mattila, K. (2014). Tekstiilikulttuurin tutkimus käsityötieteessä. In S. Karppinen, A. Kouhia, & E. Syrjäläinen (Eds.), *Kättä pidempää: Otteita käsityön tutkimuksesta ja käsitteellistämisestä* (pp. 191–201). Helsingin yliopisto, opettajankoulutuslaitos.

Seitamaa-Hakkarainen, P., Pöllänen, S., Luutonen, M., Kaipainen, M., Kröger, T., Raunio, A.-M., Sipilä, O., Turunen, V., Vartiainen, L. & Heinonen, A. (2007). *Käsityötieteen ja käsityömuotoilun sekä teknologiakasvatuksen tutkimusohjelma Savonlinnan opettajankoulutuslaitoksessa*. University of Joensuu.

Seppä-Heikka, M. (1985). Grains and seeds from younger Roman Iron Age excavations in Spurila. *Iskos*, *5*, 460–461.

Severa, J., & Horswill, M. (1989). Costume as Material Culture. *Dress*, *15*(1), 51–64. https://doi.org/10.1179/036121189803657325

International Organization for Standardization (2019). Textiles — Qualitative and quantitative analysis of some bast fibres (flax, hemp, ramie) and their blends — Part 1: Fibre identification using microscopy methods (ISO Standard No. 20706-1:2019).

Sihvo, H. (1969). *Karjalan löytäjät*. Kirjayhtymä.

Silpala, E. (1990). Kenttätyö ja esineanalyysi Artelogian tutkimusmenetelminä. *Artelogi*, *1990*(1), 7–48.

Sipilä, O. (2012). *Esiliina aikansa kehyksissä: Moniaikaista tekstiilikulttuuria ja representaatioita kodista, perheestä, puhtaudesta ja käsityöstä 1900-luvun alkupuolen Suomessa*. University of Eastern Finland.

Skoglund, G. (2020). Construction and Reconstruction of the Past: The Medieval Nordic Textile Heritage of Hemp. In M. L. Wright, R. Netherton, & G. R. Owen-Crocker (Eds.), *Medieval Clothing and Textiles 16* (1st ed., pp. 67–84). Boydell and Brewer Limited. https://doi.org/10.1017/9781787446915.004

Skoglund, G. (2021). Traditional Fine Homespun Hemp Linen Fabrics: About Qualities and Usages in Ritual and Secular Contexts. *TEXTILE*, 1–20. https://doi.org/10.1080/14759756.2021.1966726

Snellman, A. (2021). Kolonialismi-keskustelun häivytetyt ristiriidat ja liberaalidemokratian tulevaisuus. *Historiallinen Aikakauskirja*, *2021*(3), 361–365.

Snellman, A., Vajanto, K., & Suomela, J. (2018). The Professorial Uniform of Elias Lönnrot: Russian Imperial Materiality in Finland. *Artefactum*, *9*.

Splitstoser, J. C., Dillehay, T. D., Wouters, J., & Claro, A. (2016). Early pre-Hispanic use of indigo blue in Peru. *Science Advances*, *2*(9), e1501623. https://doi.org/10.1126/sciadv.1501623

Strlič, M. (2018). Heritage Science: A Future-Oriented Cross-Disciplinary Field. *Angewandte Chemie International Edition*, *57*(25), 7260–7261. https://doi.org/10.1002/anie.201804246

Suomela, J. (2020). *Phulkari Textiles from India: In Close Examination* [Master's thesis, Univerisity of Helsinki]. https://helda.helsinki.fi/items/URN:NBN:fi:hulib-202012155173

Suomela, J. A., & Lipkin, S. (in press). A button, a hook and a rug paper wrapping - Identifying plant fibre finds from Hailuoto, Finland. In F. Coletti, V. Forte, C. Margariti & S. Spantidaki (Eds.), *Multidisciplinary Approaches for the identification and preservation of Fibres and Textile Products in the Archaeological Field*. Springer.

Suomen Tekstiili & Muoti ry, & Owal Group Oy. (2022). *Tekstiili- ja muotialan kasvun paikat*. https://www.stjm.fi/wp-content/uploads/2022/05/Tekstiili-ja-muotialan-kasvun-paikat-raportti.pdf

Taitoliitto. (2022, March 14). *Neliömetri pellavaa – ryhdy perinteen kasvattajaksi*. https://www.taito.fi/kasityoohjeet-ja-jutut/artikkelit/neliometri_pellavaa/?fbclid=IwAR1EDPR1xdNtB841IfqEExdzNYph6pX2VgqFO2yuk8Kd8tUtp7fc21mZWTc

Talja, M. (2021). Miten vältellä toiseuttavia representaatioita? *www.museopro.fi*. https://www.museopro.fi/fi/miten_valtella_toiseuttavia_representaatioita

Thygesen, L. G., & Asgharipour, M. R. (2008). The effects of growth and storage conditions on dislocations in hemp fibres. *Journal of Materials Science*, *43*(10), 3670–3673. https://doi.org/10.1007/s10853-008-2587-0

Tolonen, M. (1978). Palaeoecology of annually laminated sediments in Lake Ahvenainen, S. Finland, I. Pollen and charcoal analyses and their relation to human impact. *Annales Botanici Fennici*, *15*(3), 177–208.

Vainonen, P. (2019). Kysymyksiä kulttuuriperinnön repatriaatiosta. *Kulttuurista Perinnöksi*, *2019*. https://www.kulttuuristaperinnoksi.fi/2019/kysymyksia-kulttuuriperinnon-repatriaatiosta

Vanhanen, S. (2020). Roman Iron Age and Migration period plant cultivation at Salo Isokylä, south-western Finland. In *Archaeobotanical studies of past plant cultivation in northern Europ* (pp. 131–143). Barkhuis Publishing.

Vartiainen, L. (2014). Artefaktien merkitys roolipelaajille ja historiaharrastajille. *Artefactum*, *4*.

Viljanen, M., Suomela, J. A., & Svedström, K. (2022). Wide-angle X-ray scattering studies on contemporary and ancient bast fibres used in textiles – ultrastructural studies on stinging nettle. *Cellulose 29,* 2645–2661. https://doi.org/10.1007/s10570-021-04400-w

Virrankoski, P. (1963). *Myyntiä varten harjoitettu kotiteollisuus Suomessa autonomian ajan alkupuolella (1809-noin 1865)*. Suomen historiallinen seura.

Walton Rogers, P., & Eastwood, G. (1988). *A brief guide to the cataloguing of archaeological textiles* (4th ed.). Institute of Archaeology Publications.

Wright, K., Pasanen, M., & Sojonen, E. (2023). Recreation of the medieval intarsia textile from Masku church, Finland. In S. Lipkin, E. Ruhl, & K. Wright (Eds.), *Interdisciplinary Approaches to Research of North and Central European Archaeological Textiles. The Proceedings of the North European Symposium for Archeological Textiles (23rd–26th August 2021 in Oulu)*. Masf, 12, (pp. 63–72). Archaeological Society of Finland.