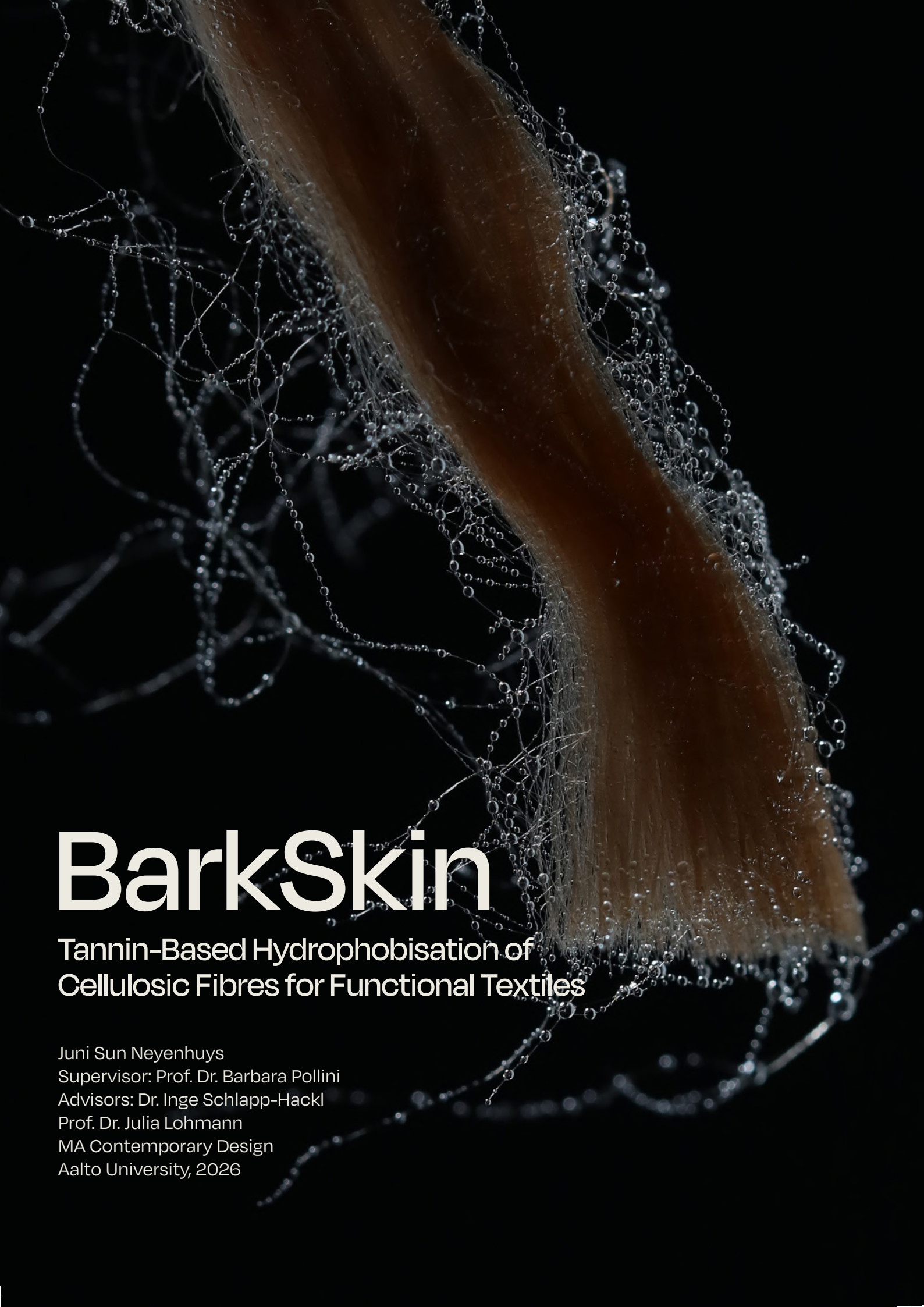


BarkSkin

Tannin-Based Hydrophobisation of Cellulosic Fibres for Functional Textiles

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MA Contemporary Design
Aalto University, 2026

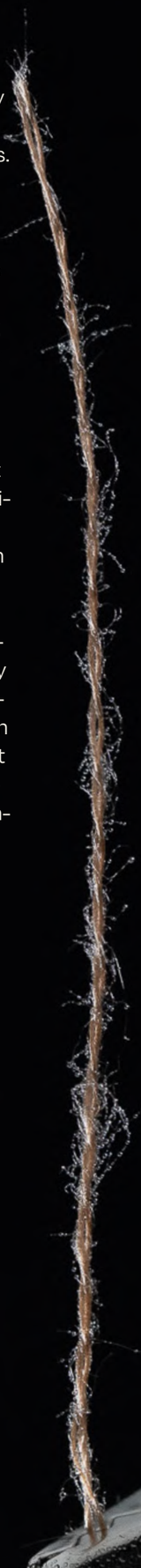
Abstract

Modern outdoor and activewear enable us to experience nature while protecting us from rain, wind, and changing weather conditions. However, these high-performance textiles heavily rely on fossil-based synthetic fibres and water-repellent finishes, which contribute to global microplastic pollution throughout their life cycle. In contrast, fibres such as regenerated cellulosics are renewable and biodegradable but remain unsuitable for many functional textile applications because of their intrinsic hydrophilicity.

Inspired by tree bark, which protects trees through naturally occurring tannins, this thesis explores whether these protection principles can be translated into textile fibres. This thesis investigates whether tree-derived tannins can be incorporated into regenerated Ioncell fibres to reduce their hydrophilicity, thereby providing a bio-based, biodegradable, and circular alternative to synthetic hydrophobic fibres.

Positioned at the intersection of fibre engineering and design, the research combined experimental material development with application-oriented design research. In the material research strand, tannins were incorporated into spinning dopes and processed into Ioncell fibres using dry-jet wet spinning. The resulting fibres were characterised through mechanical testing before being processed into yarns and textile samples for hydrophobicity evaluation. The material research was complemented by literature review, market research, and qualitative expert interviews to explore potential application fields of the developed BarkSkin fibre. The research was further translated into a speculative design outcome: an immersive multimedia installation that communicates the environmental motivations (Activism), the material research and development (Actuation), and the potential future applications of BarkSkin (Activities).

The results show that tannins can be successfully incorporated into Ioncell fibres while maintaining promising fibre quality and mechanical properties. Hydrophobicity tests point to a significant reduction in water uptake, although the fibres have not yet achieved the hydrophobicity required for water-repellent textiles. The study further reveals that part of the incorporated tannin remains water-soluble within the fibre matrix, highlighting bio-based crosslinking strategies as an important route for future research. Based on the literature review, market research, and expert interviews, the thesis identifies activewear as the most promising application field, offering the strongest overlap between the material's performance, environmental relevance, and market potential. Beyond material development, the thesis reflects on the author's dual role as a materials engineer and designer, demonstrating how scientific methods and design methods can complement one another throughout the material innovation process. By integrating these perspectives, the thesis demonstrates that scientific experimentation and design are not separate stages of material innovation but complementary ways of understanding, developing, and translating emerging materials into meaningful applications through the power of design and storytelling.



Acknowledgements

Before diving into this thesis, I would like to thank everyone from the fields of science and design who supported, guided, and inspired me throughout this journey, helping to bring this project to life.

I would like to begin by thanking my supervisors, Prof. Barbara Pollini and Prof. Julia Lohmann, for encouraging and supporting the unconventional, interdisciplinary approach of this thesis at the intersection of fibre engineering and design. Thank you for your guidance throughout the process and for helping me navigate my dual role as both materials engineer and designer.

My gratitude also goes to my advisor and close project partner, Dr. Inge Schlapp-Hackl, whose positivity, trust, dedication, and scientific expertise shaped this project from beginning to end. I am equally grateful to Prof. Michael Hummel for welcoming me into the Fibre Spinning Team and for his openness to interdisciplinary collaborations between material science and design. I would also like to thank everyone in the Fibre Spinning Team for generously sharing their expertise and for always being willing to help me in the lab.

I would also like to thank Anna van der Lei for being a thoughtful sparring partner for interdisciplinary ideas and discussions throughout the project.
My sincere thanks also go to Carla Rotenberg for weaving the textile samples with me and for being a valuable partner in feedback throughout the process, and to Johanna Hehemann for her support in knitting the textile samples.

A very special thank you goes to the talented Touch Designers, Julia Zambrzycki and Calvin Suarez, for bringing my vision for the third film, "Activities", to life with such creativity, patience, and dedication. I am equally grateful to Omid Fröhlich, Greta Ballschuh, and Minken Stenersen for serving as the trail-running models featured in the films, and to Kilian Schneider and Tom Schneider for composing the beautiful original music.

I would also like to thank all interview participants for sharing their expertise and industry insights. Although they remain anonymous in this thesis, their perspectives were invaluable in shaping the application-oriented part of this research.

Finally, I would like to thank Kilian Schneider, Frank Neyenhuys, and Stefanie Jotzo-Neyenhuys for their persistent encouragement and support through the ups and downs of this project.

Declaration of AI Use

Generative artificial intelligence tools were used for background research (Perplexity) and the writing process of this thesis to support proofreading (Grammarly) and to improve the structure of the text (Aalto AI). All scientific content, analyses, interpretations, arguments, and conclusions were developed independently by the author. All AI-generated suggestions were critically reviewed and verified, and all cited sources were consulted and evaluated independently.

Content

Abstract
Acknowledgements
Declaration of AI Use

1 Introduction 01

1.1. Framework and methods
1.2. Structure of the thesis
1.3. Motivation & Background

Part 1 Activism

2 Problem: the broken textile system 13

3. Hydrophobic fibres and textiles 19

3.1. Fundamentals of hydrophobicity
3.2. Applications of hydrophobic textiles
- 3.2.1. Water resistance
- 3.2.2. Water repellency
- 3.2.3. Waterproofness
- 3.2.4. Testing hydrophobicity
- 3.2.5. Water management of hydrophobic fibres

4. Man-made cellulose 29

4.1. Regenerated cellulosics: From viscose to Ioncell
4.2. Ioncell: A new generation of regenerated cellulose
4.3. Wood as a cellulosic feedstock
4.4. Bio-based hydrophobisation strategies for Ioncell
4.5. Tannin as a hydrophobising agent.

Part 2 Actuation

5. Material research 41

5.1. Materials
5.2. Methods
- 5.2.1. Dope preparation
- 5.2.2. Polarized light microscopy
- 5.2.3. Rheology
- 5.2.4. Dry-jet wet spinning (small scale)
- 5.2.5. Dry-jet wet spinning (scale-up)
- 5.2.5. Dry-jet wet spinning (scale-up)
- 5.2.6. Spin finish treatment
- 5.2.7. Yarn spinning
- 5.2.8. Fibre characterisation
- 5.2.9. Yarn characterisation
- 5.2.10. Weaving
- 5.2.11. Knitting
- 5.2.12. Water contact angle measurement

5.3. Results and discussion
- 5.3.1. Preparation and rheological properties of the spinning dopes
- 5.3.2. Spinnability of tannin-containing dopes
- 5.3.3. Tannin retention within the fibre
- 5.3.4. Mechanical performance of the fibres
- 5.3.5. Mechanical performance of the yarn
- 5.3.6. Hydrophobic performance
- 5.3.7. Summary

Part 3 Activties

6. Future applications 63

6.1. Potential applications in home textiles
6.2. Potential applications in outdoor and activewear apparel
6.3. Potential applications in footwear
6.4. Selecting activewear as the initial application field

7. Critical discussion on material innovation 75

7.1. Material innovation as one part of a systemic transformation
7.2. Rethinking the end-of-life narrative
7.3. Looking beyond biodegradability
7.4. Responsible sourcing of biomass
7.5. Position of this thesis

Part 4 Design & Reflection

8. Designing future material narratives 83

8.1. Translating the research into an immersive installation

9. Reflection: Between science and design 89

9.1. Negotiating ownership
9.2. Learning to think like a scientist
9.3. Rediscovering the role of the designer
9.4. Concluding reflection

10. Conclusion 95

11. References 99

1 Introduction

Living in a country such as Finland offers a unique proximity to nature. Even from the centre of Helsinki, it takes me less than twenty minutes to reach a forest. I can run for kilometres among big, old trees, breathing fresh air and experiencing the seasonal changes. In winter, activities can continue through cross-country skiing, snow hiking or ice skating. Spending time outdoors is widely recognised as beneficial for both physical health and mental health. In Japan, “Shinrin-yoku”, translated as “forest bathing”, describes the practice of spending time in forest environments to support psychological and physiological well-being.(Miyazaki, 2018). Similarly, initiatives such as those by the Finnish Forest Therapy Centre promote nature-based activities to restore well-being (Visit Finland, n.d.). These practices reflect the fact that humans are inherently connected to nature, especially as urban lifestyles increasingly distance us from it.

At the same time, a striking contradiction is evident. While we engage in health-conscious activities in nature, we rely heavily on technical garments made almost entirely from synthetic, fossil-based materials. These high-performance textiles are engineered to provide protection and comfort in changing environmental conditions. They protect against wind and rain, regulate moisture, and improve physical performance. In the short term, their functionality is highly effective. However, the environmental effects of these materials are significant. Most functional textiles are not designed with their end of life in mind. During use and washing, they release microplastics into aquatic and terrestrial ecosystems. In addition, many water-repellent finishes rely on per- and polyfluoroalkyl substances (PFAS), highly stable and toxic chemicals. Once released, they persist and disperse in the environment, causing long-lasting environmental and health risks (Doyle et al., 2024, p. 4). They are now detected in human blood and in remote ecosystems, including Arctic wildlife. Thus, the same materials that enable comfortable, safe interaction with nature also cause its degradation.

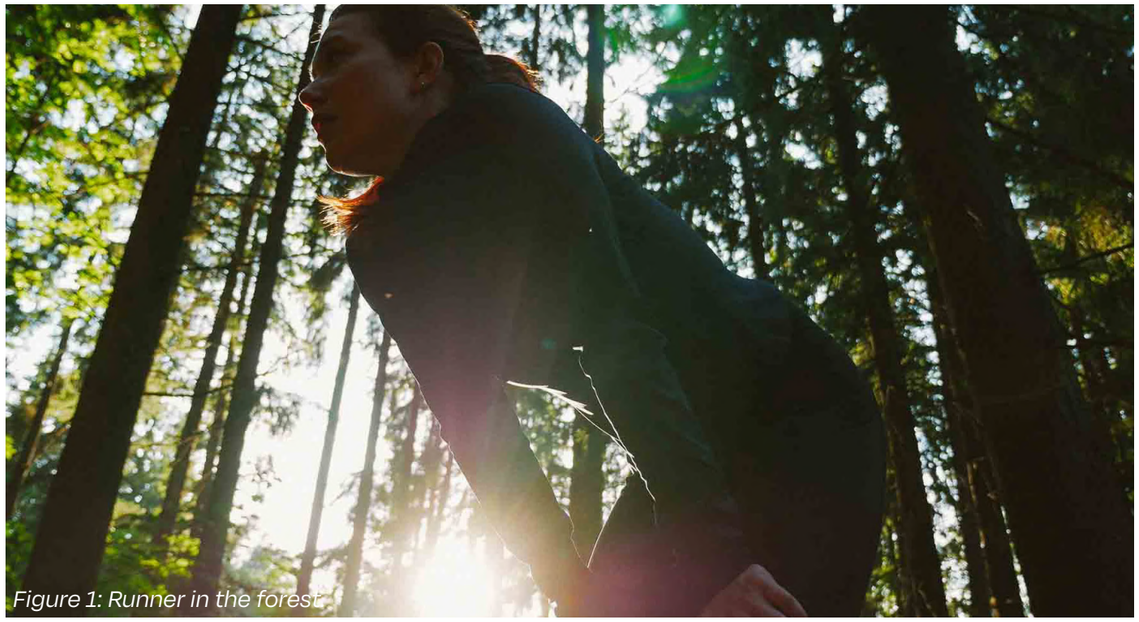


Figure 1: Runner in the forest

Natural fibres, while biobased and biodegradable, remain challenging to implement in functional clothing, particularly in activewear and outdoor applications. This limitation is largely because of their inherent hydrophilicity. Plant-based fibres such as cotton, as well as regenerated cellulosic fibres, readily absorb moisture, which can feel uncomfortable, increase garment weight, and reduce thermal performance. As a result, they are generally unsuitable for uses that require effective water repellency and moisture management unless treated with a hydrophobic synthetic coating. This limitation highlights a key gap in the development of sustainable functional textiles. Addressing this gap demands rethinking how performance properties, such as hydrophobicity, can be achieved using bio-based, biodegradable materials. This is particularly relevant as the global demand continues to grow, with the activewear market projected to reach €301–392 billion by 2025 (Materials Market Report, 2024).

In nature, protective functions are often realised through material compositions that are both biobased and biodegradable. Tree bark, for example, functions as a protective outer layer, shielding the tree from moisture, pathogens, and environmental stress (Ben Abda et al., 2025). Tannins, naturally occurring polyphenols in tree bark, contribute to this protective function. Building on this natural concept, the thesis investigates whether Ioncell, a regenerated cellulosic fibre produced through a closed-loop, non-toxic spinning process, can be hydrophobized using tannins extracted from tree bark. In doing so, it explores how to expand the potential of regenerated cellulosic fibres for functional textile applications. The project examines whether two forest-derived materials – cellulose and tannin – can be combined to create a biodegradable, circular, hydrophobic alternative to synthetic hydrophobic textiles.

In the material research strand, Ioncell fibres are produced by the dry-jet wet-spinning process, with tannins incorporated directly into the spinning dope. The resulting fibres are then processed into yarns and textile samples to evaluate hydrophobicity and mechanical properties and to compare them with those of standard Ioncell fibres. Alongside this, the design strand explores possible applications through market research and qualitative interviews with industry experts. These insights are combined with speculative design and visual storytelling to examine future use scenarios and to position the material within the contexts of functional textiles.

The thesis is structured through the triad of Activism, Actuation, and Activities. Activism addresses the wider socio-ecological need to develop novel, cellulose-based hydrophobic fibres, situating the research within the environmental challenges caused by fossil-based performance textiles. Actuation focuses on the research and development of tannin-incorporated Ioncell fibres, while Activities explores the future application potential of the material. The triad is communicated through a design-led approach, using visual storytelling to convey (1) the urgency of the problem, (2) the material innovation process, and (3) potential futures of the developed fibre. Guided by the intelligence of natural systems and framed within the circular bioeconomy, the thesis ultimately seeks to expand the range of ways to create functional, water-repellent fibres from renewable resources that reintegrate into biological cycles.

Figure 2: Tree-derived tannin

1.1 Framework & Methods

This thesis is situated at the intersection of fibre engineering and design, operating along the triad of resource, material, and product. It combines engineering methods (such as laboratory-based fibre production, spinning-dope formulation, contact-angle measurements, and mechanical testing) with design-based methods (such as qualitative interviews, market research, literature review, visual storytelling, and speculative design).

Together, these methods can be situated in an interdisciplinary, co-design-inspired framework that aligns the development of tannin-Ioncell fibres with the principles of the circular bioeconomy and the Biomimikry Life Principles. The circular bioeconomy aims to replace fossil-based resources with renewable biological materials while ensuring that these resources remain in circulation for as long as possible through reuse, recycling, and biological degradation, thereby reducing waste and environmental impact (Ellen MacArthur Foundation, 2019).

The biomimicry life principles are a useful lens for evaluating whether a design and its materials work in harmony with nature's principles (Baumeister et al., 2014). In this project, several of these principles are particularly relevant: the use of readily available materials and energy is reflected in the reliance on wood as a locally sourced, renewable resource abundant in Finland.

The principle of leveraging cyclic processes is addressed through the regenerated cellulosic Ioncell fibre, which is designed to biodegrade at end-of-life and re-enter natural biological cycles, breaking down into benign constituents without releasing toxic residues. Furthermore, unlike conventional viscose production, the Ioncell process supports closed-loop manufacturing: the process is based on life-friendly chemistry, using non-toxic, recyclable solvents and water as the coagulation medium.

Alongside these Biomimikry Life principles, the project also engages with material development through the frameworks of Technology Readiness Level (TRL) and Customer Readiness Level (CRL) (Buchner et al. 2019) (Figure 3 and 4). The research begins at early TRL stages, progressing from conceptual development (TRL 1–2) to proof of concept at the laboratory scale (TRL 3). In parallel, CRL is used to assess potential user adoption and market alignment, complementing the technological trajectory with insights into real-world applicability. While CRL is primarily oriented toward commercialisation, this thesis incorporates industry interviews to bridge the gap between early-stage material innovation and future use cases.

Figure 3: TRL According to Buchner et al. (2019)

9	**Production**	Product from production plant ready for sale
8	**Commissioning**	Product integrated, full sale plant constructed
7	**Demonstration & Full-scale Engineering**	Sample production in Pilot Plant
6	**Pilot Trials**	Working Pilot Plant
5	**Detailed Process Development**	Parameter & Property data in Laboratory
4	**Preliminary Process Development**	Application of PoC in Labodatory broadened
3	**Proof of Concept (PoC)**	PoC in Laboratory demonstrated
2	**Concept**	Technology concept formulated
1	**Idea**	Applications based on basic research result identified

Figure 4: CRL According to RawMaterials "SME Booster" (2019)

9	**Wide Sales**	Widespread Product Sales
8	**First Product sold**	First Full Product sold
7	**Test Sales**	Extended testing and first test sales
6	**Testing**	Benefits trough Partnerships & tested confirming
5	**Relations**	Relations to interested target customers established
4	**Confirmation**	Problems & Needs from several customers confirmed
3	**Feedback**	First Market feedback established
2	**Identification**	Specific needs identified
1	**Idea**	Possible Market needs hypothesized

The project is structured around three interrelated fields that form a triadic interplay: Activism, Actuation, and Activities (Figure 5). Activism raises the meta-question: Why is there a need for novel, hydrophobic, cellulose-based fibres? It situates the work within the socio-ecological context of fossil-based hydrophobic performance textiles and their environmental impacts. Actuation focuses on the What and How: It is the actuation of the material research phase, in which tannin-modified Ioncell fibres are developed and evaluated through a layered, onion-skin methodology. Activities explores and speculates about potential applications of the fibre based on market research. This triad connects material innovation with design-led communication and environmental activism, forming an interrelated, practice-based framework that bridges science, design, and sustainability.

The framework also draws on Rihimäki's notion of "user-centred knowledge" in design-driven material innovation. She argues that imagining future markets, consumer needs, and socio-environmental trends helps to define the goals, scope, and directions of material development, and even to exclude certain development paths. In this sense, the thesis adopts a futures-oriented, storytelling-based approach: speculative scenarios and visual narratives are used not only to communicate results but also to actively shape the future material development process itself. This interdisciplinary perspective also informed the interview approach adopted in this thesis, where conversations with industry experts explored not only technical material requirements but also future application scenarios, user needs, and the role of storytelling in communicating material innovation. (Niinimäki, 2019).

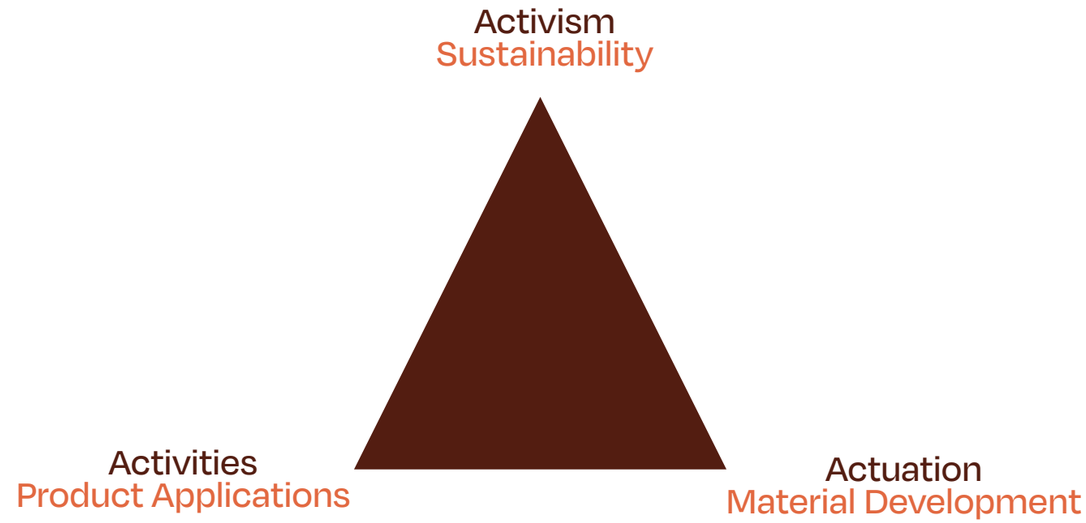


Figure 5: The triad of the thesis

To address the research questions, the thesis integrates scientific and design-based methods within the Activism–Actuation–Activities structure.

Part 1: Activism (Why)
At the meta-level, Activism investigates the environmental and systemic issues of current hydrophobic fibres and the textile system. The research question is: Why do we need novel hydrophobic cellulose-based fibres for the circular bioeconomy?

Methods include market research and literature review to analyse trends and regulatory developments in functional textiles.

Part 2: Actuation (What and How)
The second strand, Actuation, addresses the scientific research question: Can tannins be incorporated into Ioncell fibres to achieve a hydrophobic fibre that could potentially replace synthetic hydrophobic fibres in the future?

The research follows a layered, onion-skin methodology (Figure 6), in which each phase builds on the previous one:

Layer 1: spinning dope & fibre development
Tannins are incorporated directly into the cellulose–ionic liquid spinning dope at varying concentrations. The resulting dopes are spun on the laboratory-scale dry-jet wet-spinning machine using a monofilament spinneret.

The target fineness of the fibre is 1–3 dtex per filament, which is required for clothing applications. The resulting fibres are analysed for mechanical properties and compared to standard Ioncell fibres.

Layer 2: yarn production
In the second step, fibres are produced in greater quantities on the larger spinning unit and spun into yarns. The mechanical performance of these yarns is again tested and compared with that of the Ioncell reference yarns.

Layer 3: textiles & hydrophobicity
The yarns are woven and knitted into small textile samples for hydrophobicity testing (contact angle measurements) and to evaluate the overall appearance of the material, including sensory and visual properties.

Layer 4 (scaling up to pilot-scale fibre and yarn production), Layer 5 (producing textiles in larger formats), and Layer 6 (developing a final product and wearable prototype) will not be peeled within the short time frame of this thesis but represent the logical next steps if the results are promising.

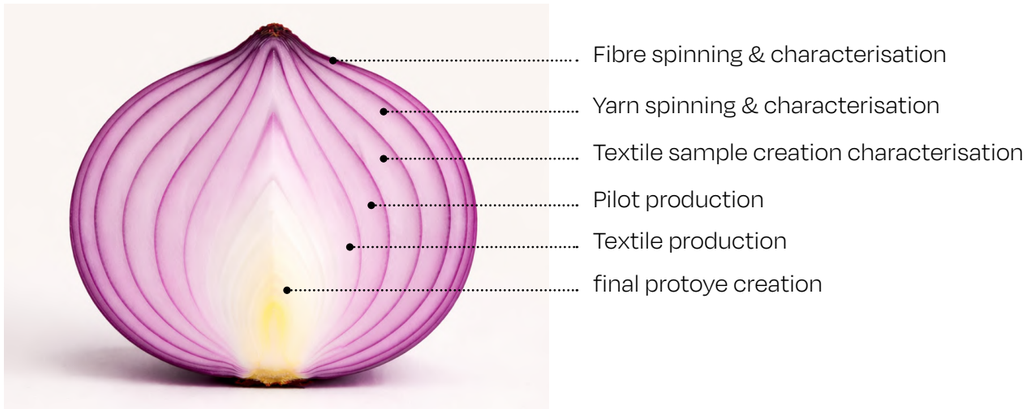


Figure 6: The onion skin methodology

Part 3: Activities (What for – Applications and Future Scenarios)
The third part, Activities, focuses on potential future uses of the fibre. It involves reviewing the literature and conducting market research on functional textiles, activewear, and outdoor fabrics, as well as qualitative, semi-structured interviews with industry experts and researchers in textiles and materials. These interviews seek to gather insights into current needs, challenges, and expectations around hydrophobic textiles. By aligning the achieved fibre properties with market insights, the thesis aims to explore future applications and to propose strategic directions for further material development.

Part 4: Design part & reflection

Design Part
How can I creatively communicate the research and development process, results, and material properties through design and storytelling? The practical design component of the thesis will present the triad of Activism–Actuation–Activity through a multimedia collage, exhibited as an immersive video and sound installation. The goal is to convey the R&D process, showcase future applications, and spark curiosity and excitement by making desirable material futures accessible to non-scientific audiences. This approach exemplifies how design-led communication can serve as both a research method and an outcome, embedding futures thinking, storytelling, and speculation into the material innovation process itself.

Reflection
In this project, although I have previously worked in various interdisciplinary constellations at the intersection of materials science and design, I take on a dual role for the first time. On the one hand, I act as a materials engineer, developing the fibre and analysing it in the laboratory. On the other hand, I assume the role of a designer, translating the processes and outcomes of the material research into a different context. In a conversation, Prof. Julia Lohmann described this duality as having “a heart divided into two parts”: one half representing the materials engineer, the other the designer.

Between them lies the material, or the fibre, acting as a separating wall (Figure 7). Depending on which role I slip into, the perspective shifts significantly. The final part of this thesis is dedicated to a personal reflection that offers insights and lessons learned from inhabiting this dual role.



Figure 7: The dual role

1.2. Structure of the thesis

The thesis is divided into four parts. Part 1, Activism, starts with problem framing, situating the work within the socio-ecological context of fossil-based hydrophobic (outdoor) performance textiles and their environmental impacts. It also provides an overview of regenerated cellulose fibre, hydrophobic fibres and textiles. Part 2, Actuation, examines the material research in which tannin-modified Ioncell fibres are developed, from fibre spinning and testing to yarn spinning and textile production. Part 3, Activities, sheds light on potential applications of the fibre. Part 4 explains how the research was translated into the practical design component and concludes with a reflection on the dual role.

1.3. Motivation and Background

During my Master's studies in Contemporary Design at Aalto University, I deepened my focus on the intersection of biomaterial innovation, design, and circularity. My practice centres on developing applications from regenerative raw materials that can seamlessly reintegrate into natural cycles. In previous projects and through mujō, the company I co-founded with a materials engineer, I have worked on developing fully bio-based and biodegradable packaging materials derived from seaweed (Figure 8). With a background in Textile Design from my Bachelor's degree, I have also worked in the textile field, developing seaweed-based fibres and, more recently, building an open-source wet spinning machine (Figure 9). This machine empowers designers to experiment with biobased fibres without the need for costly research and development infrastructure.

At mujō, my role has involved extensive material research, collaboration with scientists in the lab, the development of continuous production processes, evaluation of material properties, filing patents, and engaging with scientific literature and research funding applications in partnership with research institutes. The packaging industry faces a challenge parallel to that of the textile industry: Materials must provide effective barrier properties to protect products yet be rapidly compostable and biodegradable after disposal.

I find this interdisciplinary role especially stimulating. Positioned between science and design, I am neither a specialist scientist nor solely a designer, but rather someone who bridges the two fields. I combine reading and interpreting academic research with conducting experiments, while using design methods to translate material innovations into products, concepts, and future scenarios. This dual perspective has fundamentally shaped both the research process and the methodological framework of this thesis and is examined in greater depth in *Chapter 9: Reflection – Between Science and Design*.

My motivation for this research stems from a frustration shared by many designers today: the lack of materials that enable products to align with ecological values without compromising performance. This frustration sparked an initial determination to explore alternative materials by myself. Over time, however, I have come to recognise that technological advances alone are insufficient. The adoption of new materials is shaped by broader economic, political, and regulatory systems, and innovations rarely succeed without considering these surrounding conditions. Consequently, material innovation must be understood as one component of a wider systemic transformation of the textile industry (see Chapter 7: Critical Discussion: Material Innovation within a Systemic Transformation).

Within this context, I believe that designers occupy a unique position. By working across disciplines, they can translate scientific discoveries into meaningful products, experiences, and future scenarios while balancing ecological responsibility, technical feasibility, economic viability, and human desirability. This thesis therefore approaches material innovation not only as a scientific challenge but also as a design challenge: developing novel fibres is only one part of the process. Equally important is conceiving how these materials can become relevant, desirable, and ultimately adopted within society. This interdisciplinary position ultimately forms the foundation of the methodological framework presented in this thesis, where scientific material development and design are intrinsically linked.



Figure 8: Seaweed-based packaging materials

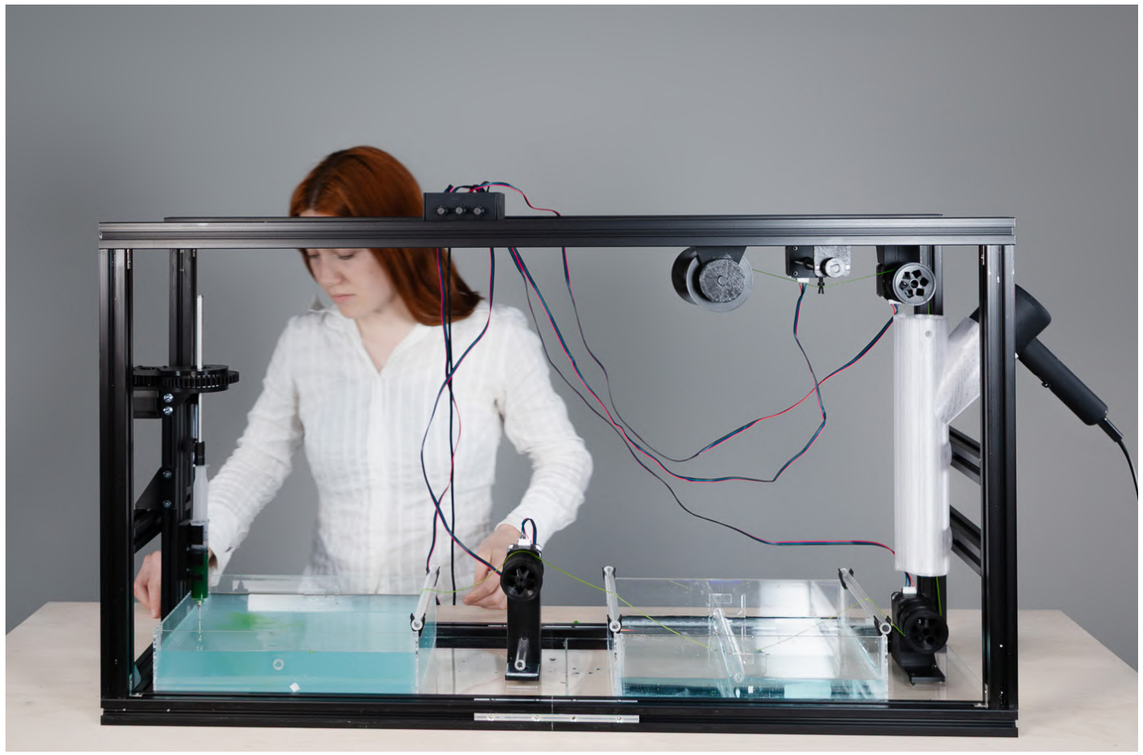


Figure 9: Open source wet biofibre spinner

PART_1

Activism

2

Problem: the broken textile system

To understand the motivation behind this research, this chapter outlines the environmental challenges associated with fossil-based performance textiles, explores the limitations of current circular strategies, and identifies the development of hydrophobic bio-based fibres as a potentially impactful opportunity for future textile systems.

Textiles are one of the oldest human technologies. Around 34,000 years ago, wild flax was used to make early yarns. Natural fibres derived from plants like flax, hemp, and cotton, or from animals such as wool and silk, have shaped clothing and shelter for millennia. Less than a century ago, the invention of plastics transformed the global fibre and textile industry into one that heavily depends on crude oil. Today, the most commonly used fibre globally is polyester, accounting for 60% of total fibre production (Statista, 2024).

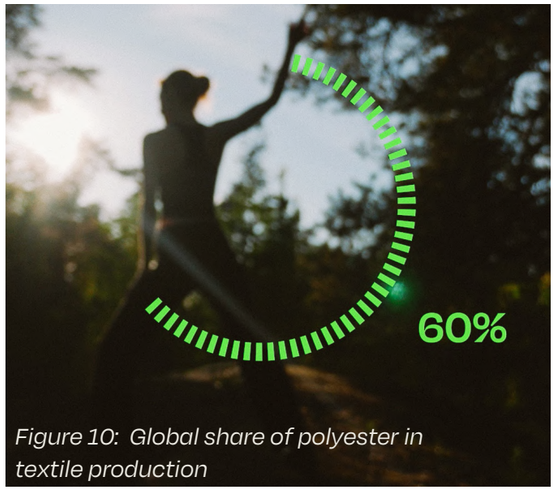


Figure 10: Global share of polyester in textile production

The rapid replacement of natural fibres by synthetic, fossil-based alternatives can be attributed to several properties and manufacturing advantages. The first advantage lies in the versatility of synthetic polymers. Fossil-based fibres are made of long-chained carbon polymers that can be engineered in a very flexible way by customising the chain length, crystallinity, or by adding functional groups (Gould & Horvath, 2023).

Second, in addition to their tailored design possibilities, all synthetic fibres are malleable and can therefore be produced using the same method: melt spinning. This uniform method makes synthetic fibres producible on an industrial, cost-efficient scale with consistent quality, giving them a major advantage over natural fibres..

A further factor in the success of synthetic fibres is their properties. Polyester, polyethylene, elastane, and nylon are extremely strong, durable, abrasion-resistant, and inherently hydrophobic. In combination, these characteristics are particularly suitable for functional textile applications, such as outdoor and sportswear, protective workwear, home textiles, and automotive interiors. In particular, hydrophobicity, which describes a very low affinity for water and low water uptake, is an important feature. Hydrophobic fibres repel external moisture, such as rain, while enhancing comfort by transporting moisture from inside the textile to the outside, where it can evaporate quickly. This dual functionality is essential for sportswear and outdoor applications (see chapter 3, Hydrophobic fibres and textiles, for a detailed discussion).

Despite the listed valuable qualities, fossil-based, synthetic fibres possess significant drawbacks. Beyond the fact that they are based on a finite fossil resource that takes millions of years to regenerate, these fibres cause severe environmental consequences at all stages of their lifecycle. The molecular stability of synthetic fibres is a key factor that contributes to the durability of the product, enabling the textile to maintain its shape and performance over many washing cycles. However, every laundering releases small amounts of fibres that end up in groundwater and subsequently open waters. Instead of decomposing like natural fibres, they resist degradation and contribute to microplastic accumulation (Figure 11). The European Environment Agency estimates that synthetic textiles account for approximately 35% of primary microplastics released into the environment (European Environment Agency, 2022).

Tony Andrady, a chemist at the American Research Triangle Institute, sums up the situation in one sentence: "Every little piece of plastic manufactured in the past 50 years that made it into the ocean is still out there somewhere because there is no effective mechanism to break it down" (Weiss, 2006). Microplastics, invisible to the human eye and ranging in size from 5 mm to 50 nanometers, accumulate not only in marine ecosystems but also in the food chain and subsequently in the human body: they are detected in the bloodstream, the brain, and even in fetuses (Roslan et al., 2024). The effects of microplastic accumulation in the bodies of animals, humans, and plants still require extensive research. However, studies have already demonstrated that it can cause dysfunctions and disorders in animal bodies (European Commission, 2019, p. 19).

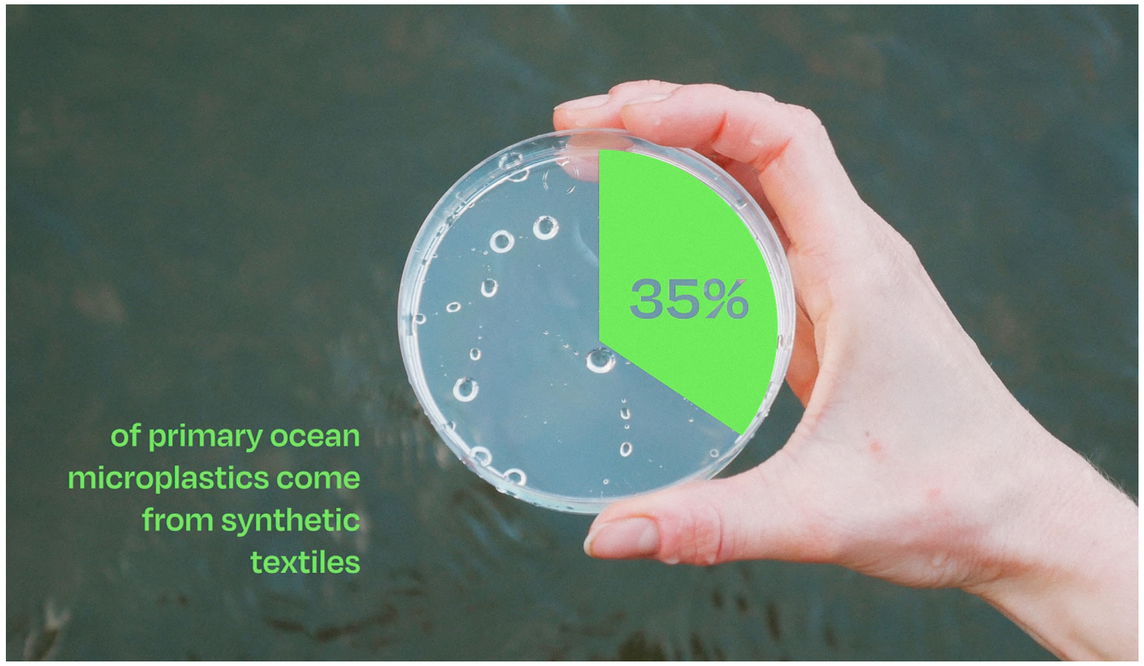


Figure 11: Textiles' contribution to ocean microplastic pollution

Another major issue in the textile industry is the use of hydrophobic treatments, which make materials waterproof, water-repellent, and oil- and stain-resistant. Thus far, the industry has relied on Durable Water Repellent coatings or finishes (DWRs), which have primarily been fluorocarbon-based. Invented by the plastics industry in the 1940s, fluorocarbon-based polymers (known as PFAS) are extremely non-stick and chemically stable, making them attractive for a wide range of applications. A well-known application of this material is the Teflon pan. The properties of PFAS have also made them a common finishing agent in textiles, where they are used to create durable water repellency. Therefore, the textile industry accounts for approximately 35% of the global fluorocarbon-based polymer demand (Doyle et al., 2024, p. 4). Similarly to synthetic fibres, the exceptional stability of PFAS is also their main downside. Throughout their lifecycle - from production and use to the end of life tiny PFAS particles are released into the environment. Because they resist degradation, they persist for long periods, disperse through air and water, and accumulate in the food chain (Figure 12). As a result, PFAS have been detected even in remote and untouched environments, which is why they are often referred to as "forever chemicals." Studies from the last decades clearly indicate the toxicity of PFAS: they cause serious health effects such as "carcinogenic effects, reproductive and organ toxicity, and immune system disorders" (Doyle et al., 2024, p. 4). The publication "The Nature of Fashion" by the Biomimicry Institute clearly summarises the current issue of the fashion and textile system: "The link between decomposition and primary production is broken, meaning that nutrients that in a natural system would be food for primary production instead become pollution" (Biomimicry Institute, 2020, p. 7). That statement highlights the current tension between performance, durability, and biological compatibility of textiles.

A particularly alarming aspect is that companies producing PFAS, such as DuPont and 3M, were aware of the harmful and toxic effects of these compounds decades ago. As early as the 1960s, internal studies involving animal testing demonstrated severe health effects, including mortality (Quillet & Noirfalisse, 2026).

Despite these findings, the results were neither published nor communicated to regulatory authorities. After more than 50 years of widespread PFAS use, growing evidence of their environmental persistence and harmful health effects has led to increased public awareness. Notably, PFAS contamination has been detected in the blood of a large proportion of the global population, raising significant concerns about the long-term implications. This has led to the ban of certain long-chain PFAS (PFOA, PFOS, PFHxS), which are proven to be highly toxic. However, PFAS refers to a group of over 10,000 compounds, meaning many other types are still in use.



Figure 12: Visualisation of microplastic accumulation in the human body.

To address the contribution of the textile industry to global plastic pollution, the European Union has developed strategies to transform the industry into a circular economy. The circular economy is a framework that aims to eliminate waste by keeping products and materials in continuous circulation through maintenance, reuse, refurbishment, remanufacturing, recycling, and composting. Within this system, materials move through either the technical cycle, in which they are designed to be reused or recycled, or the biological cycle, in which biodegradable materials safely return to the earth as nutrients (Ellen MacArthur Foundation, 2019). So far, the textile industry has primarily focused on the technical cycle. However, only 12% of the textile waste is recycled into lower-value products such as insulation materials or composites. This practice, known as downcycling, results in recycled materials of lower quality than the original material (ENTeR – Expert Network on Textile Recycling, 2019, p. 16). Consequently, extensive efforts have been directed towards the development of chemical recycling technologies. Unlike mechanical recycling, chemical recycling breaks polymers down into their molecular building blocks, which can then be used to produce new fibres of comparable quality. Yet, despite these efforts, closed-loop fibre-to-fibre recycling accounts for less than 1% of the global textile market. One of the major barriers to effective recycling is the complexity of textile blends; mixed fibres, such as wool-acrylic combinations, are difficult to separate at scale, making technical recycling ineffective and expensive. As a result, achieving a truly closed-loop textile system remains a significant challenge.

However, even if these technical barriers could be overcome, a more fundamental limitation would remain. To date, circular approaches in the textile industry have largely centred on keeping synthetic, fossil-based materials within the technical cycle. This approach assumes that materials can be contained within closed industrial loops. However, in reality, textiles continuously release fibres into the environment. As the Biomimicry Institute argues, „The same laws of physics that drive natural material cycles make it impossible to isolate the technical ones (Figure 13). Our man-made material loops always, inevitably, leak" (Biomimicry Institute, 2020, p. 4). Within the biosphere, materials are dispersed rather than sorted and isolated (Figure 14). Consequently, recycling synthetic fibres does not eliminate microplastic pollution. As long as the industry relies on materials designed to resist degradation, microplastic leakage will continue, and fibres will accumulate in the environment. The long-term challenge, therefore, is to develop textiles that operate in harmony with the laws of nature, which is the mechanism of decomposition and dispersal (Biomimicry Institute, 2020, p. 4).

Natural fibres have experienced a "comeback," as they offer a regenerative and biodegradable alternative to fossil-based materials. More broadly, a growing demand for bio-based materials, including leather alternatives derived from mycelium, bacterial cellulose, or algae, is evident (Lee et al., 2025). However, despite their sustainability potential, these materials face significant performance challenges. One of the most important challenges is achieving hydrophobicity. In contrast to synthetic fibres, most bio-based materials and fibres are inherently hydrophilic, meaning they readily absorb water. While this hydrophilicity is often considered a performance disadvantage, it is beneficial for biodegradation. When materials absorb moisture, they become more accessible to microorganisms, which can degrade their molecular structure through a chemical reaction called hydrolytic cleavage. In this process, water molecules break down the long polymer chains into shorter chains (oligomers, eventually monomers), which microorganisms can then metabolise into basic compounds such as carbon, water, and biomass. To enhance the hydrophobicity and durability of biobased materials, they are often treated with a synthetic coating such as polyurethane. This practice highlights the tension between desired performance, on the one hand, and bio-based origin and biodegradability, on the other. Consequently, emerging biomaterials designed to reintegrate into natural cycles cannot fulfil the expectation of biodegradability while meeting performance expectations. This challenge goes beyond functional textiles and represents a broader bottleneck in the development of truly circular and bio-based material systems.

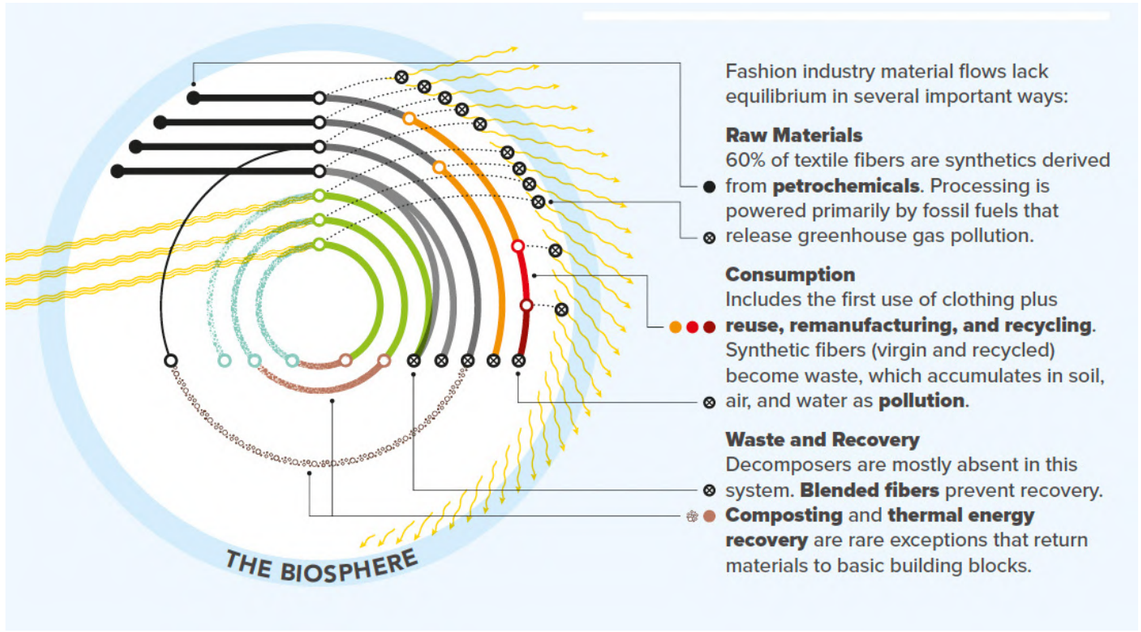


Figure 13: The current fashion system. Source: The Biomimicry Institute

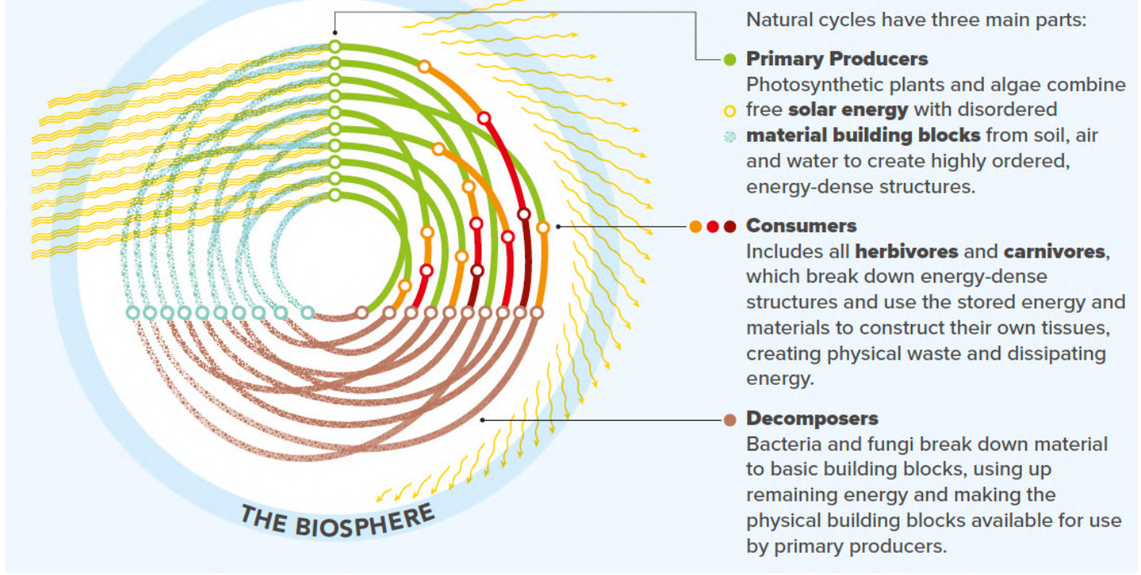


Figure 14: Natural cycle. Source: The Biomimicry Institute

3

Hydrophobic fibres and textiles

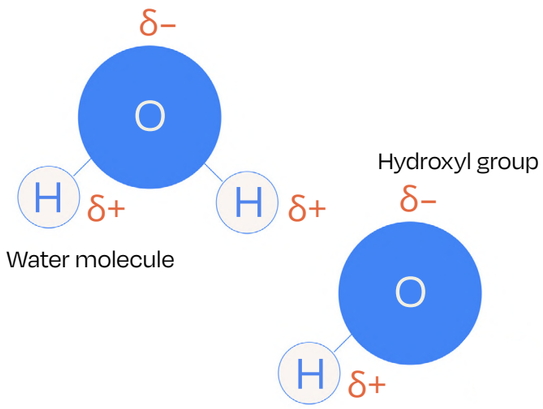
This chapter introduces the fundamentals of hydrophobic materials and their applications in textiles. It begins by explaining the molecular mechanisms underlying hydrophilic and hydrophobic behaviour, then introduces the three main categories of hydrophobic textiles – water-resistant, water-repellent, and waterproof – and their respective applications. It further examines the different levels at which hydrophobicity can be achieved within textile systems, including fibres, yarns, fabric constructions, and surface finishes. Together, these concepts provide the theoretical foundation for situating the tannin-modified Ioncell fibre within the application scenarios discussed in Part 3, Activities.

3.1. Fundamentals

The terms *hydrophilic* and *hydrophobic* originate from the Greek words *hydro* (water), *philic* (loving), and *phobic* (fearing). They describe how materials interact with water and are fundamental to understanding moisture behaviour in textiles.

At the molecular level, these interactions are governed by the distribution of electrons within a molecule. Molecules interact with each other, creating different kinds of bonds. One reason for interaction can be their electrostatic attraction, meaning two molecules have opposite charges (Figure 15). Water is a polar molecule, meaning it has an uneven distribution of electrons: the oxygen atom carries a partial negative charge, while the hydrogen atoms carry partial positive charges. This polarity enables water molecules to interact strongly with other molecules that also have polar groups (Law, 2014).

Figure 15: Hydrophilic molecules



That is why hydrophilic materials are characterised by polar functional groups, such as hydroxyl groups (–OH), which can form hydrogen bonds with water molecules. As a result, these materials readily absorb and retain moisture. Cellulose is a prominent example with many polar -OH groups that also form bonds between cellulose molecules. When water penetrates the cellulose fibre, the hydroxyl (–OH) groups in the cellulose form hydrogen bonds with water molecules (Figure 16). As these water molecules position themselves between the cellulose chains, they increase the distance between the chains, resulting in swelling (Figure 17 and 18). That is the fundamental principle of a hydrophilic fibre. This process is reversible, meaning when the fibre dries, the water molecules leave the network and the cellulose molecules re-form into a new network of cellulose-cellulose hydrogen bonds.

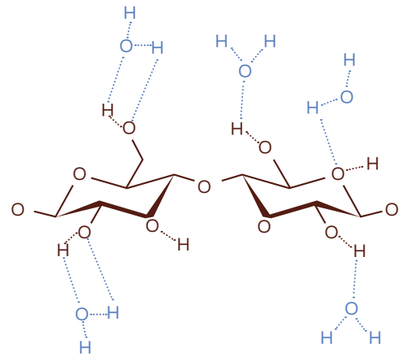


Figure 16: Cellulose structure interacting with water

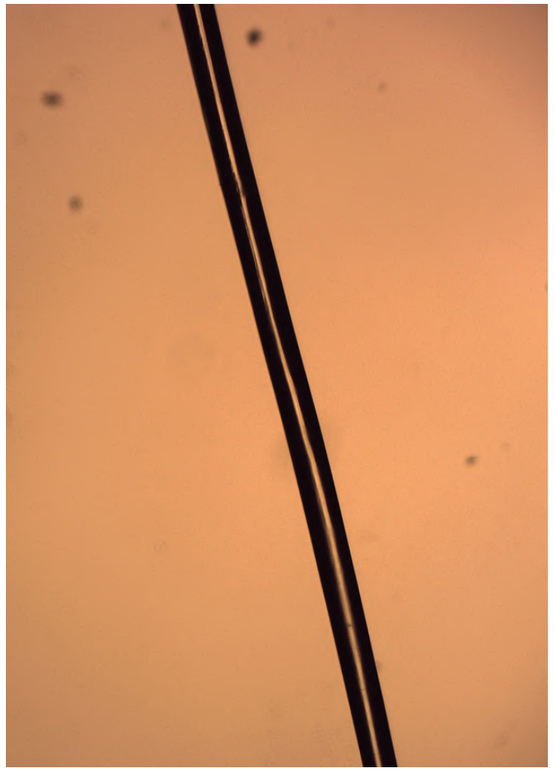


Figure 17: Microscopic picture of dry cellulose fibre

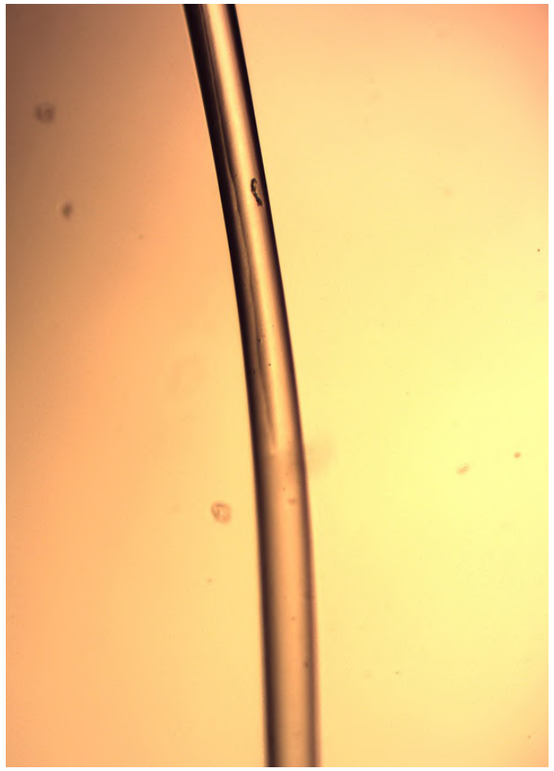


Figure 18: Microscopic picture of wet cellulose fibre

In contrast, hydrophobic materials consist of nonpolar molecular structures, in which electrons are more evenly distributed, and no partial charges are present. Typical examples include long hydrocarbon chains, such as those found in polyethylene, as well as natural substances like oils and waxes composed of fatty acids. Because these materials cannot form hydrogen bonds with water, they do not interact with it. Consequently, water remains on the surface as droplets rather than spreading or being absorbed. That explains why oil and water do not mix.

In addition to solely hydrophilic or hydrophobic materials, there are molecules that contain both characteristics. These are known as amphiphilic molecules. They contain a hydrophilic (polar) component and a hydrophobic (nonpolar) component, allowing them to interact with both types of substances (Nelson et al., 2023).

A well-known example is a surfactant (tenside), which is commonly used in soaps and detergents. Due to their dual nature, amphiphilic molecules act as intermediaries between water and nonpolar substances, enabling processes such as emulsification, which allows oil and water to mix.

Most natural plant and animal fibres are hydrophilic (for example cotton, silk, wool), while most synthetic fibres are naturally hydrophobic unless modified or coated. Building on this understanding of hydrophobic mechanisms, the following section examines their applications in the textile industry.

3.2. Applications of hydrophobic textiles

Hydrophobic fibres are widely used across a range of textile applications. To understand their role, it is necessary to consider the general behaviour of moisture and water management in textiles. Textile materials and clothing systems can be viewed as functional semi-permeable membranes that regulate heat and moisture exchange between the human body and the environment.

Hydrophobic textiles serve two primary functions. First, they provide protection against external moisture by preventing or limiting rainwater penetration into the fabric. Second, they play an important role in moisture management, influencing the transport of sweat and the drying behaviour of the clothing system.

In the textile market, hydrophobic fabrics are commonly classified into three categories based on their performance: water-resistant, water-repellent, and waterproof (Figure 19). These categories represent increasing levels of protection against water, ranging from materials that temporarily resist moisture to fabrics that repel water and, finally, to textile systems that completely prevent water penetration, even under pressure.

The hydrophobicity and overall performance of a textile are determined by several hierarchical building blocks in its construction, including the molecular composition of the material to the fibre, the yarn, the fabric structure, and the finishing processes (Figure 20). Although hydrophobicity can be influenced at multiple structural levels of a textile, the classification of fabrics as water-resistant, water-repellent, or waterproof is primarily based on their dominant mechanism of interaction with water and their resulting performance (Watkins & Dunne, 2021).

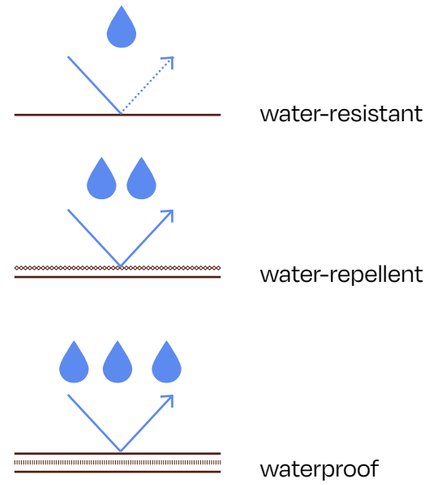


Figure 19: categories of hydrophobic textiles

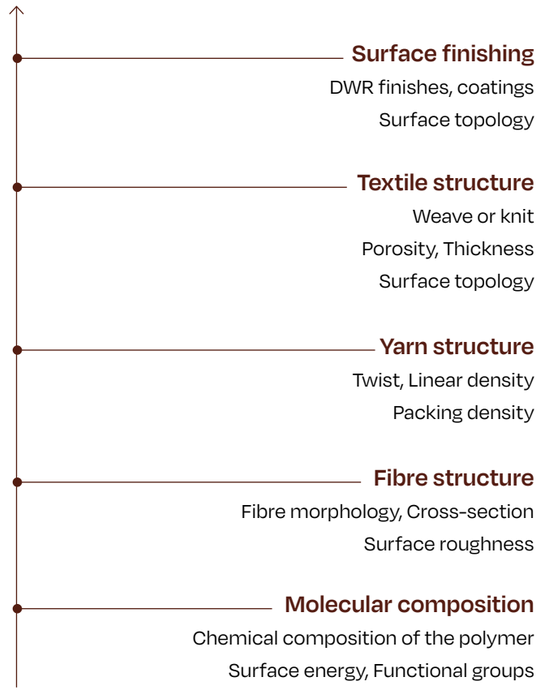


Figure 20: Hierarchical levels influencing hydrophobicity

3.2.1. Water-resistance

Water-resistant fabrics slow down or limit water penetration but are not fully leak-proof under strong or prolonged exposure. They can withstand light rain, splashes, or brief contact before water eventually passes through. Rather than completely blocking water, these textiles delay its passage (Watkins & Dunne, 2021). Water resistance can be achieved using hydrophobic fibres such as polyester, nylon, and polypropylene (PP), which exhibit low water absorption. Very fine fibres, in combination with high-density yarns, can further enhance water resistance to some extent by reducing pore size within the yarn structure, making it more difficult for water to penetrate.

The same mechanism applies to textile construction. Tight weaves or knits reduce pore size, meaning that higher pressure is required for water to pass through. For example, very densely woven polyester fabrics are commonly used in water-resistant jackets. Another well-known example of a water-resistant textile based primarily on fabric construction is Ventile, developed by Shirley Cloth in the United Kingdom (Watkins & Dunne, 2021). It is produced from very fine, long-staple cotton fibres woven into a dense fabric structure. Due to the hydrophilic nature of cellulose, the fibres swell upon contact with water, causing the interstices between yarns to close and thereby significantly reducing water penetration (Figure 21).



Figure 21: tightly woven cotton

Applications for water-resistant fabrics include everyday outerwear, such as windbreakers and running jackets. They are also used in accessories, including bags, backpacks, and laptop sleeves. In home textiles, they are applied in products such as furniture covers, shower curtains, and rugs, where short-term protection is sufficient.

3.2.2. Water repellency

Water-repellent fabrics are designed to shed water, even in heavy rain. A fabric is considered water-repellent when the cohesive forces within a water droplet are stronger than the adhesive forces between the water and the textile surface. As a result, the droplet maintains its shape, beads on the surface, and can roll off rather than being absorbed (Watkins & Dunne, 2021). Water repellency is mainly achieved by surface chemistry. Materials with a low surface energy prevent water from penetrating the textile surface. While hydrophobic fibres and dense fabric structures can support this effect, they are not sufficient on their own. In practice, water repellency is generally achieved through the application of durable water repellent (DWR) finishes.

Historically, water repellency was primarily achieved using natural waxes, oils, and greases for applications such as military garments, sailors' clothing, and outdoor equipment. Although these treatments provided only moderate, often temporary protection and diminished the fabric's handle and breathability, they remained the dominant approach for centuries. This changed with the discovery of fluoropolymers in the late 1930s, when chemist Roy J. Plunkett at DuPont accidentally produced polytetrafluoroethylene (PTFE) while experimenting with tetrafluoroethylene gas (Gould & Horvath, 2023) (Figure 22).

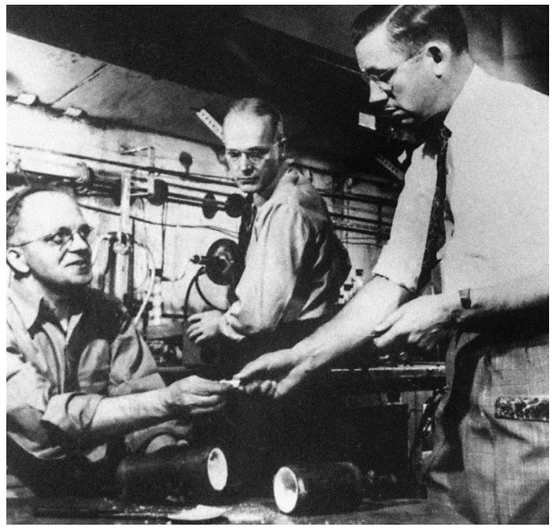


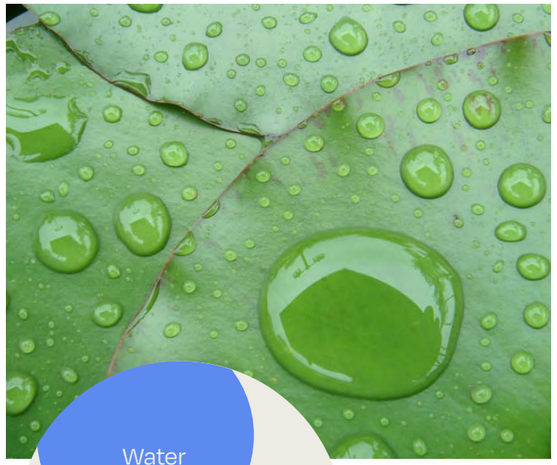
Figure 22: the invention of PTFE. Source: AP (Associated Press)

The development of fluorocarbons revolutionised water-repellent textiles by providing highly durable, invisible, and oil-repellent finishes with exceptional performance. As a result, fluorocarbon-based durable water repellent (DWR) finishes became the industry standard for outdoor apparel for decades.

In recent years, these concerns have led to increasing regulatory action in the EU (Outdoor apparel expert, personal communication, April 24, 2025). In response, alternative finishing technologies have been developed. Silicone-based finishes have a lower environmental impact than fluorocarbons, although they are not biodegradable. More sustainable approaches include hydrocarbon-based finishes, such as waxes and fatty compounds, which avoid fluorinated chemistry and provide a moderate water repellency (Chen et al., 2025). However, compared with fluorinated finishes, these alternatives offer lower durability and are less oil repellent. Wax-based finishes, in particular, may increase fabric stiffness and require more frequent reapplication.

Past conventional chemical treatments, structural approaches to water repellency draw inspiration from natural systems. The so-called lotus effect is a well-studied natural phenomenon, observed in lotus leaves and certain animal surfaces such as feathers (Figure 23). These surfaces combine low-surface-energy chemistry with hierarchical micro- and nanostructures that trap air and reduce the real contact area between water and the surface. As a result, water droplets rest on the tips of these structures and roll off easily (Figure 24). This principle has been translated into textile applications through nanoparticle-based treatments, such as silica coatings, which create similar micro–nano surface roughness. (Ensikat et al., 2011). These approaches can increase water repellency while diminishing reliance on environmentally persistent chemical finishes. However, the challenge in textiles is to maintain such delicate topography under abrasion and laundering.

Figure 23: The hydrophobic surface of the lotus leaf. Source: Biomimicry Institute.



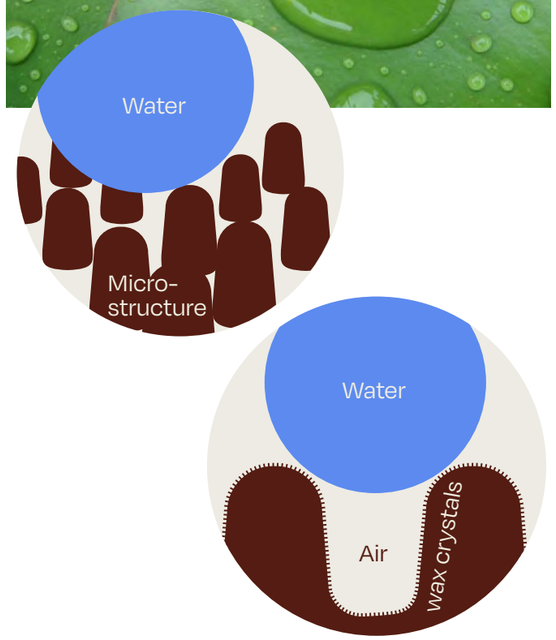


Figure 24: microscopic visualisation of low-surface-energy chemistry with hierarchical micro- and nanostructures

Water-repellent fabrics are widely used in performance outdoor clothing, such as hiking jackets and pants, ski wear, and activewear, including running jackets. They are also common in everyday casual fashion, for example in sneakers and coats. In addition, they play an important role in upholstery and home textiles, such as sofa covers, table linens, carpets, mattress protectors, and outdoor furniture. Technical applications include automotive interiors and workwear.

3.2.3. Waterproofness

According to Watkins and Dunne (2021), waterproof fabrics are designed to prevent water penetration entirely, even under pressure. In practice, this means that not only the fabric itself, but the entire system, including seams, must keep water out. Waterproof fabrics therefore typically consist of a multilayer system comprising an outer fabric, a microporous membrane (Figure 25), and an inner lining. The membranes can be laminated across the full surface. However, these fabrics are generally not breathable. Waterproof and breathable systems consist of a microporous membrane with billions of tiny pores smaller than water droplets yet large enough to allow water vapour (e.g., sweat) to pass through. A well-known example is Gore-Tex. In Gore-Tex technology, fabrics are laminated with a thin microporous layer made of polytetrafluoroethylene (PTFE), polyester or polyurethane.

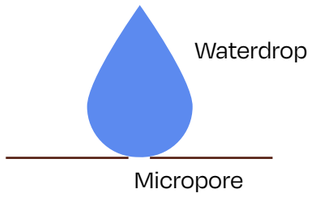


Figure 25: Microscopic visualisation of microporous membrane

Application areas for waterproof systems are highly diverse. They are widely used in outdoor gear such as waterproof footwear, ski jackets, sailing equipment, tents, backpacks, and boat covers. They also play an important role in protective clothing, including rainwear, emergency service uniforms, and medical applications. In general, they are essential wherever prolonged exposure to wind and rain must be mitigated.

Picture 26: Waterproof rainjacket



3.2.4. Testing hydrophobicity

To measure water resistance and waterproofness, the hydrostatic head (or hydrostatic pressure) test (ISO 811 / AATCC 127) is commonly used. In this method, the fabric is clamped over water, and the pressure is gradually increased until water droplets appear on the surface (Figure 27). The key observation is the pressure at which the first droplets penetrate the fabric. This pressure is reported in millimetres of water column (mmH_2O).

Moderate hydrostatic head values (e.g. ~1,000–5,000 mmH_2O) are often described as "water-resistant," while waterproof products typically achieve higher values (e.g. 10,000–30,000 mmH_2O).

Water repellency, on the other hand, can be evaluated using the contact angle test (Figure 28). In this test, a droplet is placed on the textile surface and the contact angle is measured. If the angle is greater than 90°, the surface is considered hydrophobic, while angles above 150° indicate superhydrophobicity.

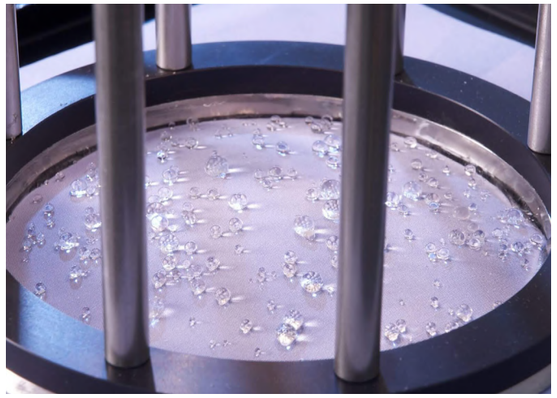


Figure 27: Hydrostatic Pressure Test. Source: Nelson Labs.

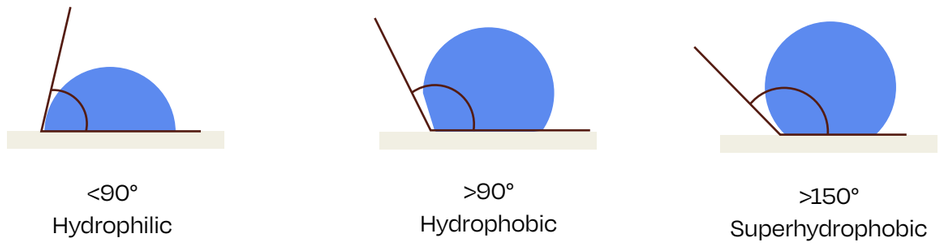


Figure 28: Visualisation of water contact angle test

3.2.5. Water management of hydrophobic fibres

Hydrophobic fibres function not only as a barrier against external water sources such as rain, but also fulfil a key role in regulating and managing moisture produced by the human body (Figure 32). Due to their low moisture absorption, hydrophobic fibres do not retain water, thereby preventing a clammy sensation and supporting rapid drying. This property is particularly critical in the activewear sector, where moisture management is a key functional requirement. Hydrophobic fibres facilitate the transportation of sweat away from the skin through a process known as wicking. Wicking is defined as "the ability of a fabric to transfer moisture adsorbed on fibres from one section to another" (Hayes & Venkatraman, 2018, p. 27). This mechanism is governed by the capillary effect, which describes the movement of liquids through narrow spaces or porous structures in the absence of external forces such as gravity.

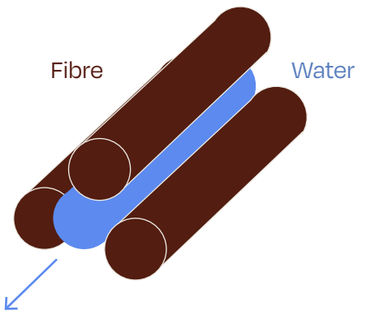


Figure 29: Visualisation of water wicking in textiles

The capillary effect results from the interaction between adhesive forces (attraction between the liquid and the solid surface) and cohesive forces (attraction within the liquid itself). When adhesive forces exceed cohesive forces, liquid is drawn along the surface, enabling directional moisture transport (Figure 29). This phenomenon allows water to move against the force of gravity and is commonly observed in natural systems, such as plants. Textile structures consist of yarns made up of fibres, within which microscopic channels exist between the individual fibres. These capillary pathways enable moisture to move from the skin-facing surface to the fabric's outer surface. Subsequently, the increased surface area and exposure facilitate evaporation, thereby improving overall moisture management performance. The finer the fibres, the higher the moisture vapour transmission.

In addition to the inherent properties of hydrophobic fibres, textile engineering strategies can further enhance moisture transport. One method involves modifying the fibre cross-section. For example, polyester fibres can be extruded into non-circular shapes, such as Y-shaped ones, which increase the available surface area and enhance capillary action. Another strategy is to alter the surface chemistry of hydrophobic fibres. Polyester, for instance, can be treated with hydrophilic finishes or blended with small amounts of hydrophilic fibres, such as cotton or cellulose-based fibres. In these cases, the hydrophilic components facilitate moisture transport along the fibre surface, while the hydrophobic core stays dry (Hayes & Venkatraman, 2018, p. 43).

Conversely, moisture management can also be achieved through inverted fibre structures. Yarns may be spun with a hydrophilic core (for example cotton) surrounded by a hydrophobic outer layer (Figure 30). The inner core absorbs and stores moisture, while the outer hydrophobic surface stays dry to the touch. As a result, the fabric maintains a dry-skin feel despite retaining internal moisture.

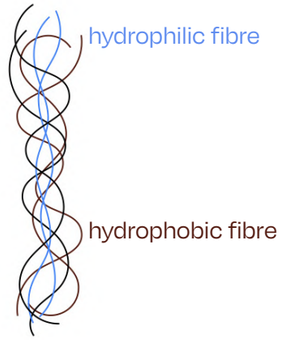


Figure 30: Visualisation of moisture wicking fibre blend

A natural example of this behaviour can be observed in merino wool. This fibre has a hygroscopic core that can absorb up to 35% of its own weight in moisture vapour. At the same time, its outer layer is hydrophobic due to the natural lanolin covering the fibre. Consequently, merino wool fabrics can absorb moisture while still providing a dry feeling (Hayes & Venkatraman, 2018, p. 42).

Finally, moisture management can also be engineered at the fabric level through different layers that create a gradient (Figure 31). These systems typically position a hydrophobic layer next to the skin to minimise wetness sensation, combined with a more hydrophilic outer layer made from fibres such as cotton or viscose. This construction creates a "push–pull" effect, in which moisture is driven away from the skin and transported to the outer surface, where it can evaporate (Hayes & Venkatraman, 2018, p. 40).

Based on the findings studied in this chapter, hydrophobic fibres have a wide range of applications and can be strategically integrated at multiple levels, including the fibre, yarn, fabric construction, and finishing stages.

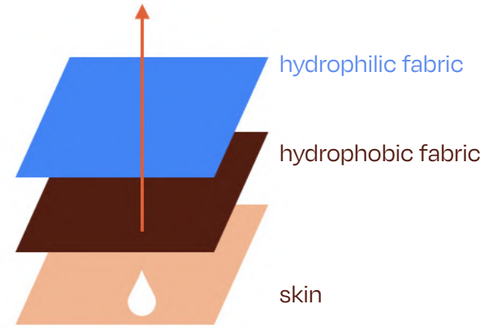


Figure 31: Visualisation of moisture wicking textile systems

Figure 32: Moisture-regulating sports bra

4

Man-made Cellulose

4.1. from Viscose to Ioncell

This chapter introduces regenerated cellulosic fibres and situates Ioncell within the broader landscape of textile fibres. It first provides an overview of the classification of textile fibres, then explains cellulose structure and the principles of cellulose regeneration. Subsequently, the chapter reviews the development of regenerated cellulosic fibres from viscose and Lyocell to the emerging Ioncell technology, explaining their production processes, environmental characteristics, and material properties. Finally, it discusses the sourcing of cellulose feedstocks and the role of sustainable forestry in supporting regenerative fibre production. Together, these concepts establish the scientific foundation for understanding Ioncell as the material platform investigated in this thesis.

Textile fibres can be broadly divided into natural fibres and man-made fibres. Natural fibres include plant-based cellulose fibres such as cotton, flax, hemp, and jute, as well as animal fibres like wool and silk. Man-made fibres, by contrast, are manufactured through industrial processes and are commonly grouped into synthetic fibres (e.g., polyester), inorganic fibres (e.g., carbon fibre), and regenerated fibres produced from natural polymers (e.g. regenerated cellulosic fibres) (Hu et al., 2020).

Cellulose is the most abundant structural molecule in the world and is found in the cell walls of nearly all plants. It is a strong and rigid biopolymer composed of the monomer D-glucose, which forms long chains through covalent β-1,4-glycosidic bonds (Figure 33). These cellulose chains are organised into ordered structures that are held together by hydrogen bonds between the –OH (hydroxyl) groups (Klemm et al., 2005).

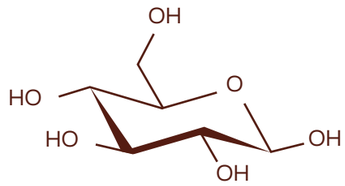


Figure 33: Momomeric unit of cellulose

There are two primary crystalline forms of cellulose. Cellulose I describes the natural crystalline form found in plant-based fibres, in which the cellulose chains are aligned in a parallel configuration. Cellulose II is the crystalline structure found in regenerated cellulosic fibres, in which the cellulose chains adopt an antiparallel arrangement. Although it has the same chemical composition as native cellulose, Cellulose II represents a thermodynamically more stable crystal structure.

Regenerated cellulosic fibres are produced by dissolving cellulose pulp and reforming it into filaments; this class includes viscose, modal, Lyocell, Tencel and newer technologies such as Ioncell. Global production of regenerated cellulosic fibres was about 7.5–7.9 million tonnes in 2023, corresponding to roughly 6% of total fibre production (Materials–Markets–Report–2024). The earliest commercial regenerated cellulose fibre was viscose, developed at the end of the 19th century. Its fundamental process consists of: steeping cellulose in sodium hydroxide, reacting it with carbon disulfide to form cellulose xanthate, and regenerating the cellulose in an acidic bath (Figure 34). Viscose can be produced efficiently at large scale. However, its reliance on carbon disulfide, a toxic and volatile compound, and its high water and energy use pose environmental and health challenges (Moriam et al., 2021).



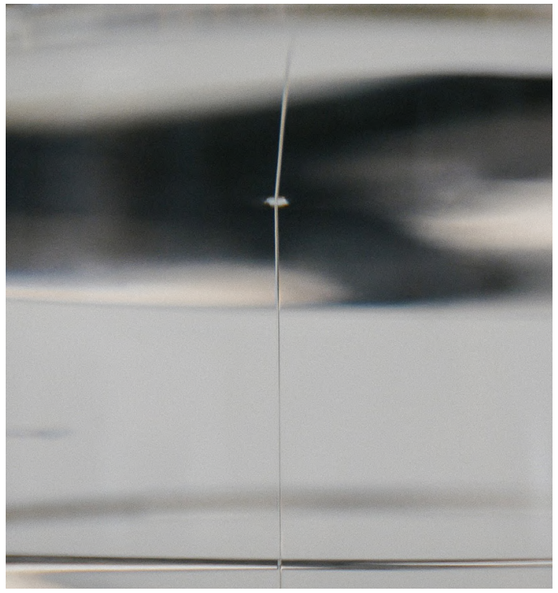
Figure 34: Viscose production. Source: Lenzing

In response to environmental concerns and stricter regulations, alternative viscose-type fibres such as Lyocell were developed. In the Lyocell process, the toxic carbon disulfide chemistry of viscose is replaced by the direct dissolution of cellulose in N-methylmorpholine N-oxide (NMMO) at temperatures of around 100 °C. Lyocell production operates in an almost closed-loop process in which the solvent can be recovered and reused at rates of up to 99%, and NMMO is generally considered to be less toxic and more environmentally benign than the chemicals used in the viscose process. Lyocell fibres are produced by dry-jet wet spinning, which enables high fibre strength and uniformity (Guizani et al., 2021). However, NMMO must be stabilised with suitable additives to prevent runaway reactions, such as explosions (Sixta et al., 2015).

4.2. Ioncell: A new generation of regenerated cellulose

Ioncell represents a new generation of regenerated cellulosics that is more sustainable than conventional Lyocell. It was developed at the Department of Bioproducts and Biosystems at Aalto University in collaboration with the University of Helsinki and uses a superbase-derived ionic liquid, 1,5-diazabicyclo[4.3.0]non-5-enium acetate ([DBNH][OAc], to dissolve cellulose at about 80-85°C. During dissolution, the water that is present in the cellulose is replaced by the ionic liquid, turning it temporarily into a malleable, honey-like spinning dope. Using dry-jet wet spinning, this dope is extruded through an air gap into a water bath, where the ionic liquid diffuses out, and water diffuses in, causing the cellulose to regenerate into continuous filaments (Guizani et al., 2020) (Figure 35). The Ioncell process reforms cellulose into a new fibre structure without chemically modifying the cellulose, meaning the fibre remains biodegradable. After regeneration, the filaments are drawn, washed, dried and cut into staple fibres, which are subsequently spun into yarns. The ionic liquid solvent is non-volatile, non-flammable, and designed for closed-loop recovery and reuse, thereby avoiding the hazardous emissions associated with viscose and the thermal instability issues associated with NMMO in the Lyocell process.

Figure 35: Ioncell spinning on lab scale



The resulting fibres (Figure 36) exhibit high tenacity and modulus together with softness and good drape, making them suitable for apparel applications. At the same time, the process can utilise diverse cellulose feedstocks such as wood pulp, recycled paper and post-consumer cotton, thereby supporting circular material flows (Figure 37). Early findings and process analyses indicate that the approach produces a much more environmentally friendly textile fibre than viscose (Guizani et al., 2021).



Figure 36: Ioncell fibres

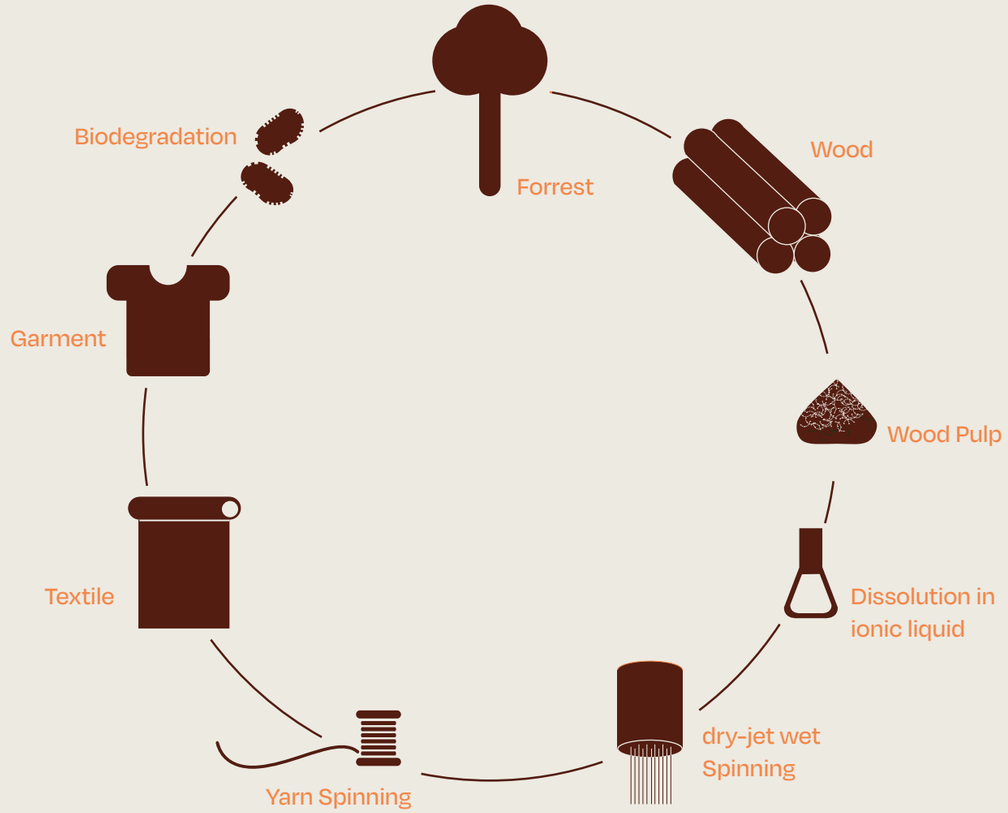


Figure 37: The lifecycle of Ioncell

4.2. Wood as a cellulosic feedstock

In principle, regenerated cellulosic fibres can be produced from any cellulose-containing biomass. In practice, however, the industry primarily uses wood species with naturally high cellulose content, as this enables the production of dissolving pulp of the high purity required for fibre-spinning processes (Regenerated Cellulosic Fibres – Viscose, Modal, Lyocell, Cupro & Triacetate, n.d.) (Figure 39). For this reason, regenerated cellulose fibres are commonly derived from hardwoods such as birch and beech in Central and Northern Europe, eucalyptus for lyocell production, and softwoods such as spruce and pine. In some cases, bamboo and cotton linters (short cotton fibres unsuitable for spinning) are also used as feedstocks (Textile Exchange, n.d.).

Responsible wood procurement can be supported through certification schemes such as the Programme for the Endorsement of Forest Certification and the Forest Stewardship Council, which promote traceability and sustainable forest management (FAO, 2020, p. 74). However, not all cellulose feedstocks originate from certified sources. Ensuring responsible sourcing is therefore essential to minimise negative impacts on biodiversity and forest ecosystems while maintaining the role of forests as important carbon sinks that contribute to climate change mitigation (FAO, 2020, p. 99).

For Ioncell, Nordic hardwood and softwood species offer particularly suitable fibre sources due to their favourable chemical composition (Figure 38). Birch, spruce, and pine typically contain 40–50% cellulose, of which about 25–40% of the total wood mass can be isolated as high-purity dissolving pulp (Shokri et al., 2022). Birch, one of the primary feedstocks explored in Ioncell research, contains approximately:

Cellulose: 40–45% of total wood, with 90–96% extractable.

Hemicellulose: 25–35%, which can be further valorised into co-products such as barrier materials, food ingredients, or biochemicals.

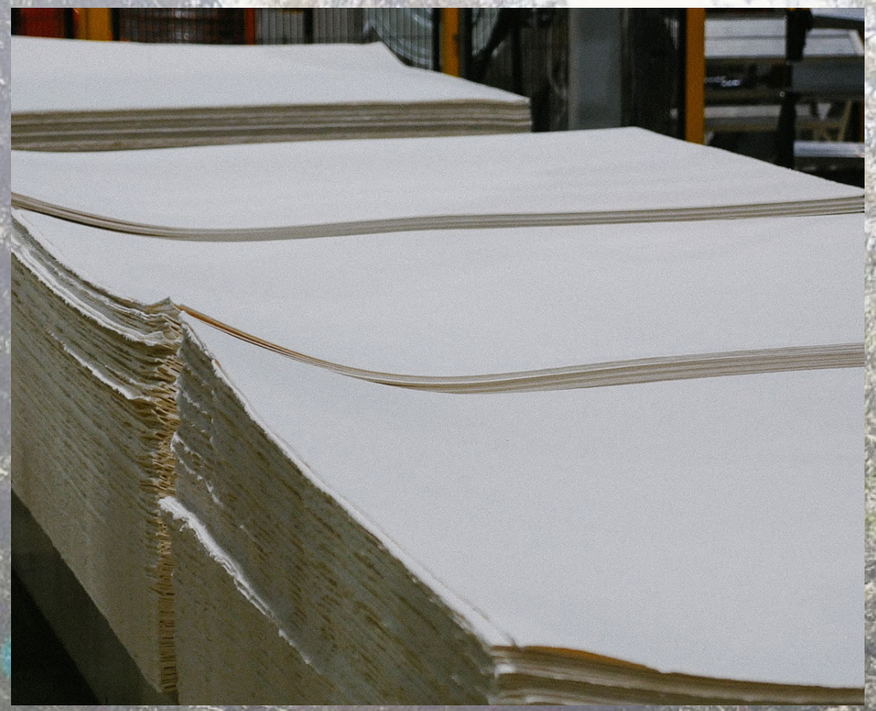
Lignin: 15–25%

Tannins and other extractives: 2–8%, concentrated mainly in the bark and heartwood

Another factor that influences the sustainability of Ioncell is the local availability of cellulose feedstock. Finland is a major producer of high-quality dissolved pulp from birch and other softwoods from sustainably managed forests, which account for about 17% of goods exports. At the same time, emerging companies such as Spinnova and Ioncell-related initiatives are building local fibre production pathways. With national wood harvests (70–75 million m^3 per year) well below forest growth (100–105 million m^3), Finland also has an estimated additional sustainable harvest potential of around 15 million m^3 annually – often cited as a capacity for expanding bio-based industries such as regenerated cellulosic fibres without compromising ecological limits. (Total Roundwood Removals and Drain by Region 2024, n.d.)

In conclusion, Ioncell fibres present a promising alternative to synthetic fibres such as polyester due to their regenerative nature, local availability, biodegradability, closed-loop production, and favourable material properties. However, their inherent hydrophilicity remains a key limitation, often restricting their performance in applications requiring hydrophobicity. Addressing this limitation is therefore essential for expanding the use of Ioncell fibres.

Figure 38 & 39: Visiting a forest site and paper pulp factory from UPM in Kouvola



4.4. Bio-based hydrophobisation strategies for Ioncell

This chapter introduces current approaches for hydrophobising regenerated cellulosic fibres and positions tannins within this emerging field of research. After reviewing existing research on bio-based hydrophobization strategies developed for Ioncell, the chapter examines the properties of tannins and discusses their potential as an internal hydrophobizing agent. Together, these concepts situate the present research within the broader context of developing sustainable water-repellent cellulosic textiles.

Cellulosic fibres are naturally hydrophilic due to the abundance of hydroxyl groups, which readily form hydrogen bonds with water molecules. As a result, they absorb moisture, which contributes to comfort in everyday use. However, the same high moisture absorption leads to longer drying times and increased fabric weight when wet, which limits Ioncell's suitability for sportswear. Consequently, cellulosic materials often underperform compared to inherently hydrophobic synthetic fibres such as polyester. Recent research has explored several bio-based strategies to impart hydrophobicity to Ioncell fibres, either by incorporating hydrophobic compounds directly into the spinning dope or by applying bio-based hydrophobic coatings (Moriam et al., 2021; Forsman et al., 2020; Guillen et al., 2026; Westerback et al., 2024).

A promising research project at Aalto University demonstrated that Ioncell fibres can be successfully hydrophobised by incorporating betulin and betulinic acid, naturally occurring triterpenes abundant in birch bark. Betulin and Betulinic acid were incorporated directly into the spinning dope at different concentrations, with 10 wt% yielding the best results. Betulin is a rigid pentacyclic triterpene with very low polarity (hydrophobic). By distributing it throughout the fibre during spinning, betulin effectively masks the water-accessible hydroxyl groups of the cellulose molecules, particularly at the fibre surface. As a result, the fibre surface has a lower affinity for water, causing water droplets to bead rather than spread and wet the surface. (Moriam et al., 2021).

This approach offers a fruitful path toward sustainable water-repellent cellulosic textiles through incorporating hydrophobic molecules in the fibre without relying on potentially harmful hydrophobic treatments. However, this research is in its early stages, and Betulin and Betulinic acid are not yet available in large quantities.

Beyond incorporating betulin and betulinic acid, other bio-based strategies have been explored to impart hydrophobicity to Ioncel fibres. One line of research focuses on surface treatment using natural waxes, achieving durable water repellency without fluorochemicals (Forsman et al., 2020). Another approach uses lignin-based dispersion coatings, in which lignin nanoparticles are combined with wax or fatty components to create hydrophobic, stain-resistant barrier layers on fibre-based substrates (Guillen et al., 2026). In parallel with these coating strategies, another ongoing research project investigates the direct incorporation of lignin, a tree component, into the spinning dope as a potential hydrophobising agent (Westerback et al., 2024). Taken together, these developments indicate a wider shift towards bio-based hydrophobisation strategies, either through incorporating bio-based hydrophobisation agents into the fibre or by applying coatings to the surface (Figure 40).

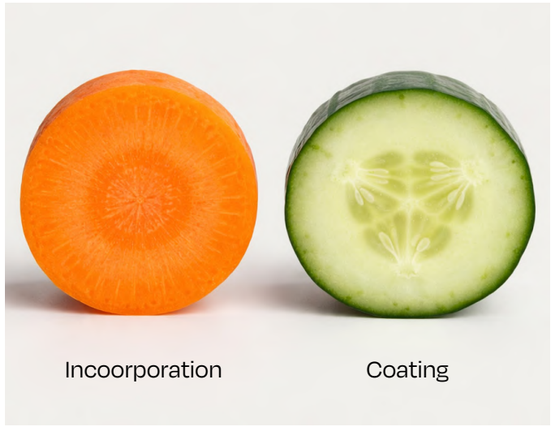


Figure 40: Visualisation of two Hydrophobisation approaches

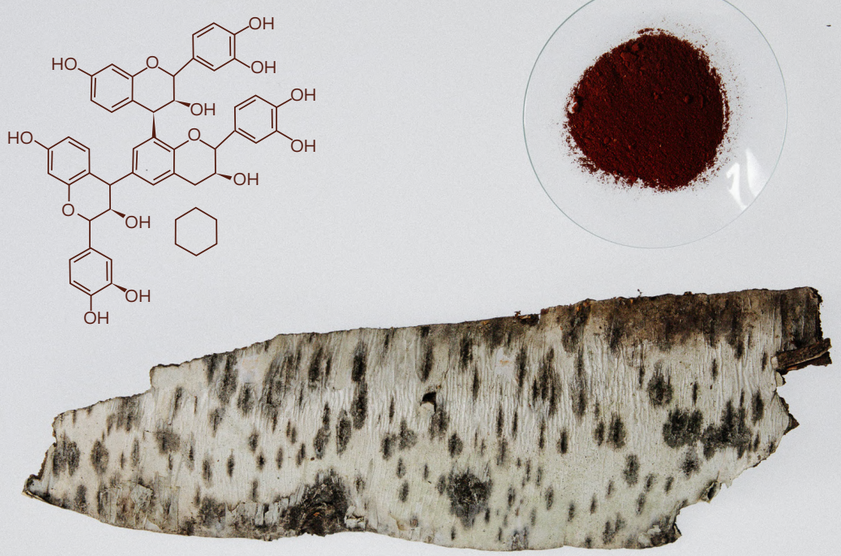
4.5. Tannin as a hydrophobising agent

Building on these concepts, the thesis investigates the potential of another naturally abundant class of plant polyphenols to hydrophobise cellulosic fibres: tannins. Tannins are a diverse group of naturally occurring polyphenolic compounds widespread throughout the plant kingdom, especially in bark, leaves, fruits, and seeds. Chemically, tannins are complex molecules rich in hydroxyl groups, which enable them to form strong complexes with proteins and other organic compounds (Figure 41). In plants, tannins play critical protective roles, including deterring herbivores, inhibiting microbial growth, mitigating oxidative stress, and providing UV protection (Ben Abda et al., 2025).

Beyond their biological functions, tannins are well known in everyday life from unripened fruits, red wine, and tea, where they contribute to characteristic astringency (the dry, puckering sensation in the mouth) as well as colour and flavour. Industrially, tannins have diverse applications. Their strong protein-binding properties make them essential for stabilising collagen fibres during leather tanning. In textile dyeing, tannins serve as natural dyes and mordants, improving dye fixation and colour fastness. In addition, their antioxidant and antimicrobial properties have led to applications in medicinal formulations (Das et al., 2020).

Unlike betulinic acid, tannins are more readily available at an industrial scale. They are often extracted as brown powders from tree bark using solvents such as hot water or water–ethanol mixtures (Ben Abda et al., 2025). Although tannins also contain numerous polar hydroxyl groups, this thesis hypothesises that these hydroxyl groups interact with cellulose hydroxyl groups via hydrogen bonding, forming a network that reduces the accessibility of the free hydroxyl groups to water. Previous studies have demonstrated the successful incorporation of tannins into cellulose films, producing materials with enhanced hydrophobic and antimicrobial properties (Missio et al., 2018). These findings suggest that tannins offer a promising renewable approach for modifying the surface properties of cellulose-based materials. The internal integration of tannins in the fibre matrix offers a potential advantage over hydrophobic coatings, which are applied to the fibre surface and wash off over time. In addition, the tannin used in this study is derived from tree bark. During conventional pulping processes, bark is removed from the logs before pulping and is commonly incinerated to generate energy for the process. Consequently, it represents an underutilised side stream of the forest industry that could serve as a renewable feedstock for functional textiles.

Picture 41: Tannin powder, Condensed tannin structure, adapted from Ben Abda et al. (2025)



Picture 42: Tree bark

PART_2

Actuation

5

Material Research

The material research explores the possibility of incorporating tannins into Ioncell fibres to reduce their inherent hydrophilicity and increase their water resistance. The experimental work comprised spinning dope preparation and characterisation; fibre spinning and mechanical testing; yarn spinning and testing; and processing the yarns into textile fabrics for hydrophobicity evaluation. This chapter first describes the materials and experimental methods used throughout the study, and subsequently presents and discusses the results obtained.

5.1. Materials

Materials used in the materials research process included the ionic liquid solvent 1,5-diazabicyclo[4.3.0]non-5-enium acetate ([DBNH][OAc]). The ionic liquid consists of positively charged $[DBNH]^+$ and negatively charged $[OAc]^-$ ions, which effectively solvate the cellulose polymer chains, enabling the pulp to dissolve into a homogeneous, spinnable dope (Guizani et al., 2020).

The additive tannin, extracted from the bark of different trees by Daniel Barker-Rothschild (University of British Columbia), was used. As a cellulose source, pre-hydrolysed kraft pulp sheets (Stora Enso Oyj) were utilised and mechanically ground into fine fibres using a Fritsch grinder. The dry matter content of the pulp (93%) and tannin (93.44%) was determined to ensure reproducibility of experiments across different laboratories with varying humidity conditions.

5.2. Methods

5.2.1. Dope Preparation

Ionic liquid was melted at 80 °C in an oven and transferred to a preheated kneader at 85 °C. For the standard dope, cellulose pulp was gradually added to the ionic liquid and kneaded for 1.5 hours at 85 °C and 30 rpm under reduced pressure (10–150 mbar) (Figure 43). The kneader was stopped after 30, 60, and 90 minutes to push the mixture down and collect small samples for microscopic analysis (Sixta et al., 2015) (Figure 44).

The dopes were prepared based on a standard formulation consisting of 87 wt% ionic liquid and 13 wt% cellulose. Tannin was added in varying amounts ranging from 2.5 to 5 wt% relative to the cellulose content. After mixing, the dope was filtered using a 6 µm metal mesh filter. For the tannin-incorporated dope, tannin was first added to the ionic liquid and stirred at 85 °C, 30 rpm, and 10–50 mbar for 10 minutes before the cellulose pulp was added. The prepared dope was stored overnight in a sealed plastic bag in a refrigerator at 5 °C prior to spinning. The total batch size for the small-scale dopes was 40 g, while the large spinning batch was approximately 870 g. Kneading time for large-scale production consisted of two 45-minute cycles.

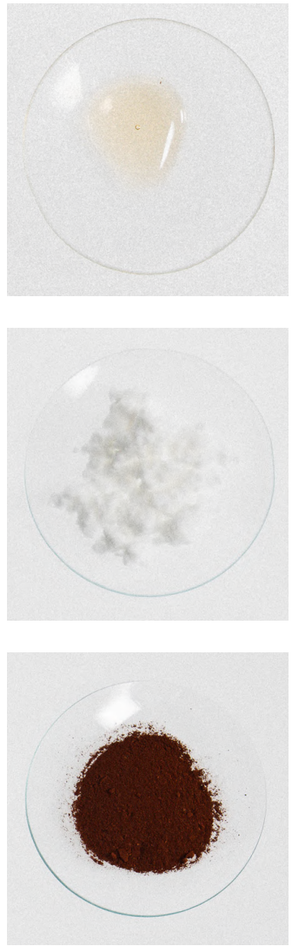




Figure 43: Dope before mixing



Figure 44: Dope after mixing

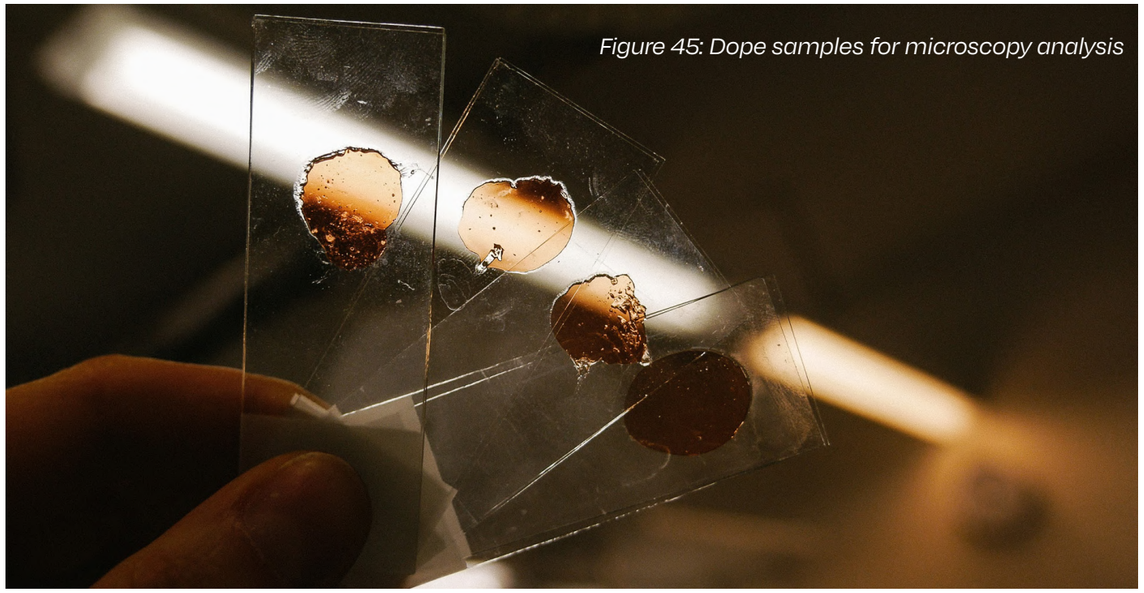


Figure 45: Dope samples for microscopy analysis

5.2.2. Polarized light microscopy

To analyse dissolution at 30, 60, and 90 minutes, followed by filtration, a transmitted-light polarisation microscope equipped with a heating stage (Zeiss Axio, LTS420) was used. The dope sample was pressed flat between two microscope slides (Figure 45).

5.2.3. Rheology measurement

Rheology plays a crucial role in the Ioncell spinning process, as it describes how the spinning dope flows and deforms under shear and elongational forces during extrusion and drawing. Viscosity characterises how thick or fluid the dope is. The elasticity indicates its ability to store and recover deformation energy, which helps to maintain a stable filament and prevents breakage. By measuring the viscoelastic properties (storage modulus G′, loss modulus G″, complex viscosity, zero-shear viscosity and the G′/G″ crossover point), the suitable processing window and optimal spinning temperature for the dope were determined. The rheological measurements were carried out on an Anton Paar MCR rheometer using a parallel-plate geometry with a plate diameter of 25 mm and a gap size of 1 mm (Sixta et al., 2015). A small sample of the dope was placed on the device, and the temperature range was 40–90 °C for the dynamic frequency sweep test (Figure 46). Measurements were conducted at 5 °C intervals over an angular frequency range of 0.1–100 s^{-1}.

The resulting data were used to determine the zero-shear viscosity (η0) by fitting the Cross viscosity model, assuming the validity of the Cox–Merz rule. In addition, the crossover point (COP), defined as the intersection of the storage modulus (G′) and loss modulus (G″), was identified. The COP characterises the viscoelastic behaviour of the spinning dope and marks the transition from predominantly viscous to predominantly elastic behaviour (Asaadi et al., 2018; Elsayed et al., 2021).

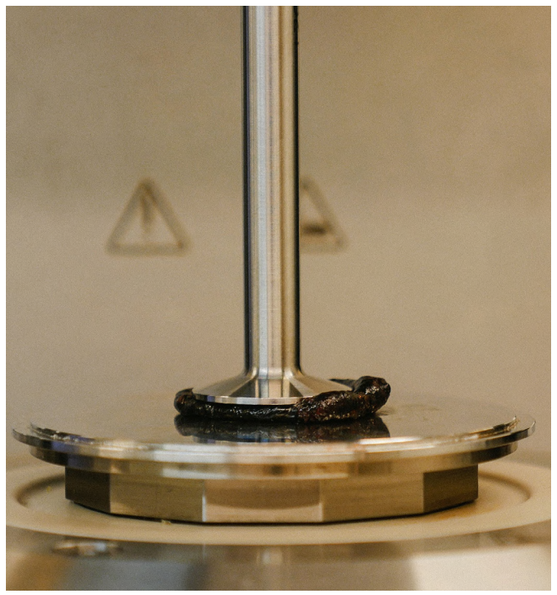


Figure 46: Rheology test setup

5.2.4. Dry-jet wet spinning (small scale)

For small-scale fibre spinning, a Dry-jet wet spinning unit by Fourné Maschinenbau GmbH, Model KS15, was used with a monofilament spinneret with a diameter of 0.1 mm. The bath temperature was 5°C, and the air gap (to stretch the fibres) ranged from 0.5 to 1 cm. The godet speed ranged from 5 to 19 m/min (Guizani et al., 2020). The collected fibres were washed three times with warm water (50°C) before being air-dried under a fume hood. To evaluate the spinnability of the dopes, spinning experiments were conducted at temperatures ranging from 55 °C to 70 °C. The optimal spinning temperatures predicted from rheological measurements were used as a guideline.

The maximum draw ratio was determined by collecting the fibre on the godets and gradually increasing it until fibre breakage occurred. Target draw ratios for textile applications range between 8 and 11. The variable process parameters (Figure 47) included spinning temperature (°C), godet speed (m/min), and, where applicable, extrusion/piston speed (cm^3/min). If a spinning dope proved to be spinnable, the aim was to collect as much fibre as possible at draw ratios of 8 and 11 for subsequent testing. The collected fibres were cut into 10 cm pieces, washed three times with water at 50 °C to remove any remaining ionic liquid, and then dried in a fume hood.

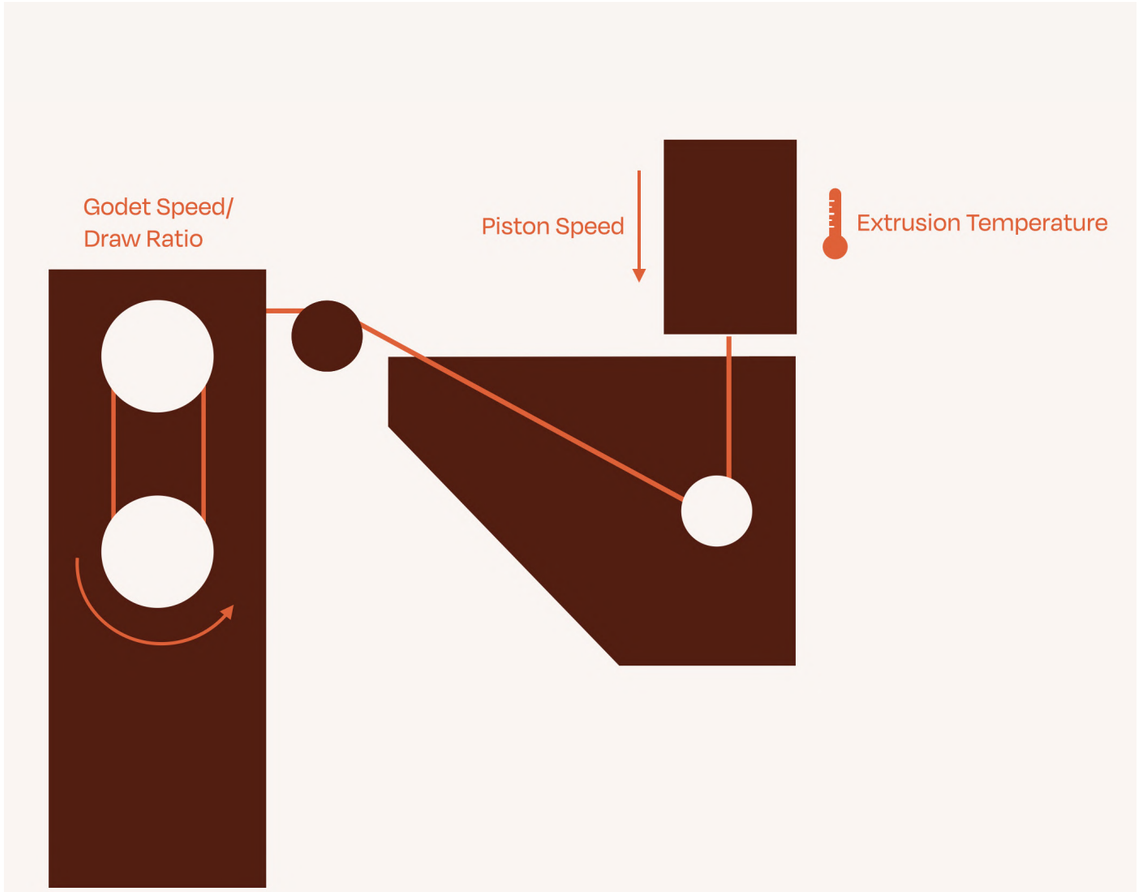


Figure 47: Small scale Dry-jet wet spinning

5.2.5. Dry-jet wet spinning (scale-up)

After identifying a suitable spinning dope on the small-scale spinning unit and determining the optimal processing parameters, fibre spinning was scaled up using the KS80 Dry-Jet Wet Spinning Line by Fourné Maschinenbau GmbH (Sixta et al., 2015). A multifilament spinneret with 300 holes, each measuring 0.1 mm in diameter, was used (Figure 49). The coagulation bath temperature was 7.6 °C, the spinning temperature was 75 °C, and the air gap ranged from 0.5 to 1 cm. The piston speed was 5.5 cm^3/min, the godet speed was 19 m/min, and the draw ratio was 8. After spinning, the fibres were cut into 4 cm pieces (Figure 50), washed three times with water at 50 °C to remove any remaining ionic liquid, and then dried on a grid tray.



Figure 49: Extrusion

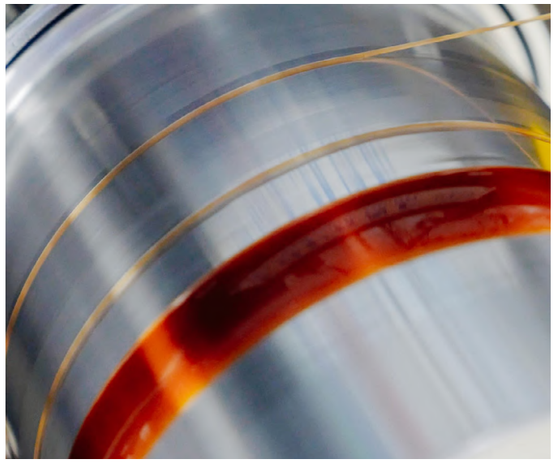


Figure 48: Fibre collecting



Figure 50: 4cm fibre pieces

5.2.6. Spin finish treatment

The fibres produced on the large-scale spinning line required treatment with a spin finish before further processing into yarns (Figure 51). The air-dried regenerated fibers were treated with a spin finish consisting of an aqueous solution of Afilan CVS (0.67 g/L) and Leomin PN (0.22 g/L) from Archroma at 50°C, using a liquor ratio of 1:20. After 5 minutes, the fibers were squeezed to achieve a 300% wet pick-up and then air-dried.



Figure 51: Drying fibres after Spin finish treatment

5.2.7. Yarn spinning

To process the fibres into yarn, several steps were required (Figure 53). The first step was fibre opening using the Trash Analyser Mesdan S.p.A. 281C. This process separated fibres that had become entangled and clumped together during previous processing steps. In addition to opening the fibre mass, the machine also removed fibres that were too short for further yarn production. Secondly, the fibres were carded using the Laboratory Carding Machine by Mesdan S.p.A. The resulting fibre web was folded several times by hand and drafted twice using the Mesdan-Lab Stiro Roving Lab machine to produce slivers (Figure 52.1 and 52.2). The slivers were subsequently converted into roving and wound onto two cones as pre-yarn. The pre-yarns were then spun using ring-spinning technology on a laboratory yarn-spinning machine by SER.MA., with a Z-twist of 650 turns per metre and a draft ratio of 34.TES S.r.l. Finally, the yarns were plied together and wound onto a single cone using an electronic winder (Rissanen et al., 2022).



Figure 52.1: Roving process

Figure 53: From fibre to yarn



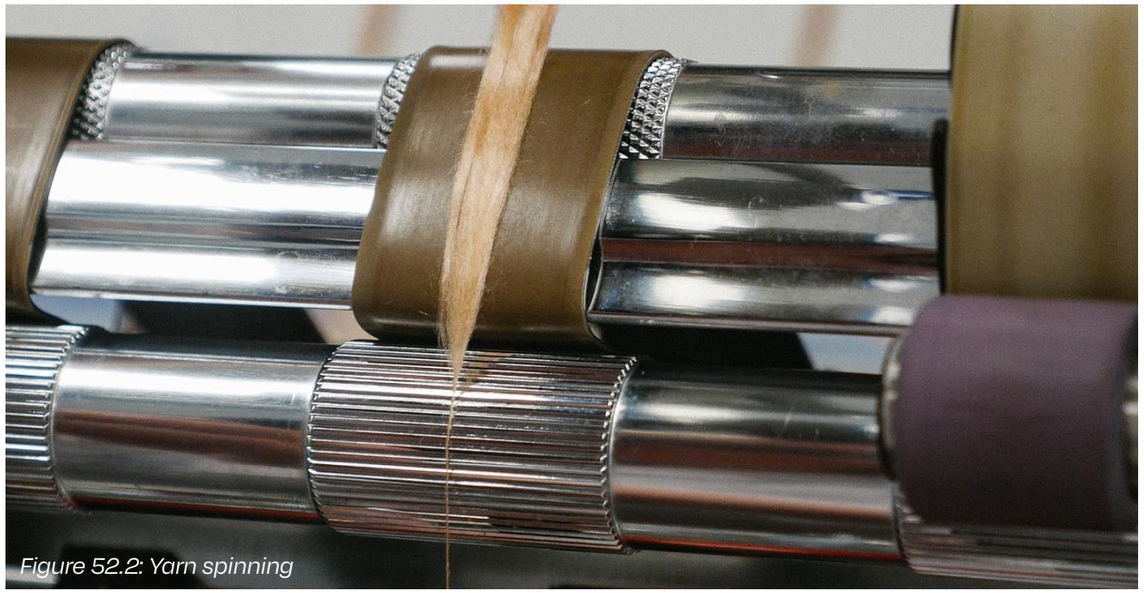


Figure 52.2: Yarn spinning

5.2.8. Fibre characterisation

The mechanical properties were tested using Favigraph instrument 178 (Textechno, Germany) under wet and dry conditions (Figure 54). Before the testing, the fibres were conditioned at 20±2 °C and 65±2 % RH overnight. Measurements were taken according to using the SFS-EN ISO 5079 (fibre count: 20 per measurement, gauge length 20 mm, and speed 20 mm/min). The used pretention weight was 100 mg. The mechanical properties of the fibres were evaluated by measuring three key parameters: (1) linear density (dtex), which describes the fineness of the fibre; (2) elongation at break (%), which represents the maximum strain the fibre can undergo before breaking, expressed as the percentage increase in length relative to its initial length; and (3) tenacity (cN/tex), which describes the tensile strength of the fibre and is defined as the maximum force the fibre can withstand before failure, normalised by its linear density. The results were compared with those reported in the literature for standard Ioncell fibres.

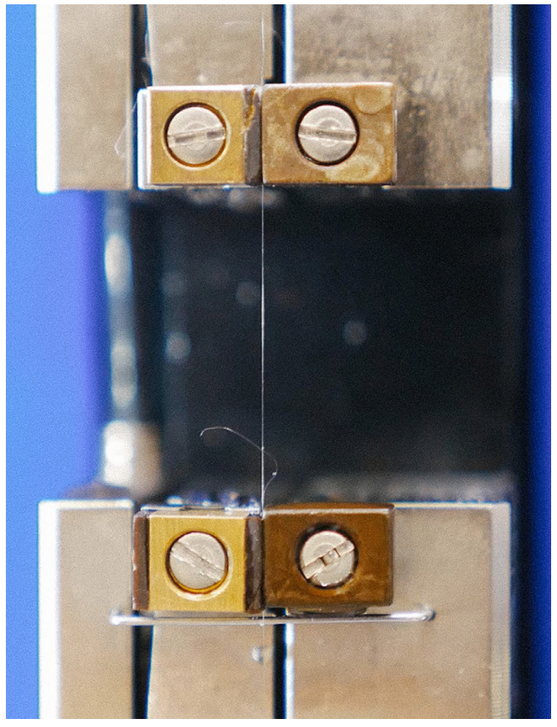


Figure 54: Dry test

5.2.9. Yarn characterisation

To evaluate the mechanical properties of the yarns, including elongation, tenacity, and linear density, tensile testing was performed 30 times using an Instron universal testing machine in accordance with ISO 139:2005, ISO 2062:2009, and ISO 2060:1994.

5.2.10. Weaving

One portion of the plied yarn was woven into a textile measuring 25 cm × 40 cm using a digital TC2 Jacquard loom by Tronrud Engineering (Figure 55 and 58). The loom was equipped with a cotton warp (Filmar M558) with a density of 36 ends per cm. A 5-harness satin weave was chosen to maximise the exposure of the tannin-containing weft yarn on the fabric face while maintaining a compact fabric structure with low porosity.

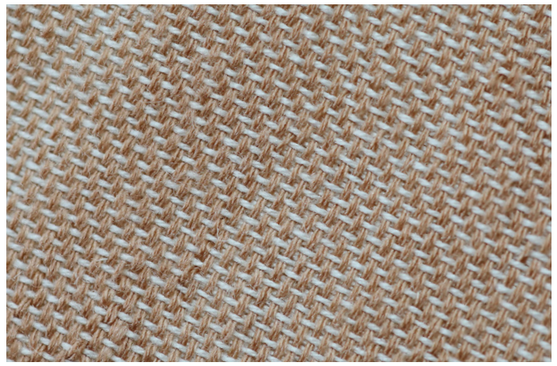


Figure 55: Woven fabric

5.2.11. Knitting

The second portion of the plied yarn was knitted on a Stoll hand-operated double-bed knitting machine using a Milano knit structure (Figure 56 and 59). Milano knit is a dense, dimensionally stable structure commonly used in activewear applications.

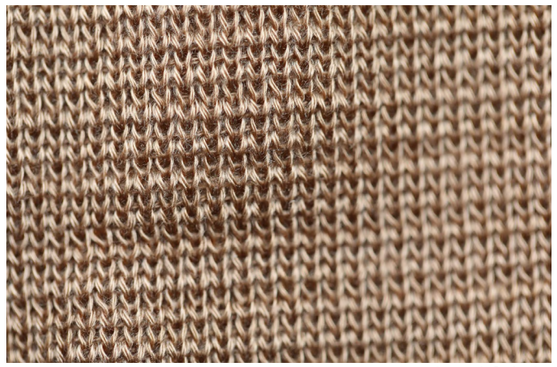


Figure 56: Knitted fabric

5.2.12. Water contact angle measurement

To evaluate the hydrophobicity of the textiles, a water contact angle test was performed. In this test, a water droplet is placed on the textile surface, and the contact angle between the droplet and the surface is measured. A contact angle greater than 90° indicates a hydrophobic surface, while a contact angle above 150° is generally classified as superhydrophobic. Contact angles below 90° indicate hydrophilic behaviour (Figure 57).

During testing, the textile was mounted in an embroidery frame to ensure that the fabric did not come into contact with the underlying surface. A water droplet was applied to the textile with a pipette and recorded on camera. As a reference material, a satin-woven fabric produced from standard Ioncell yarn was tested under the same conditions.

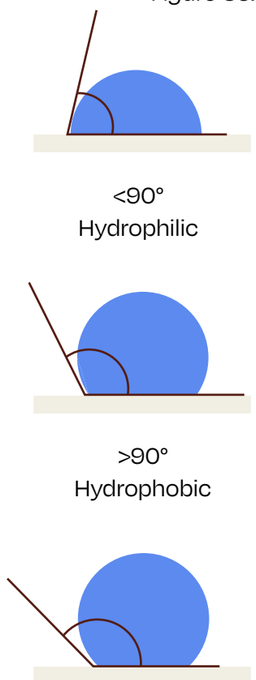


Figure 57: Visualisation of water contact angle test

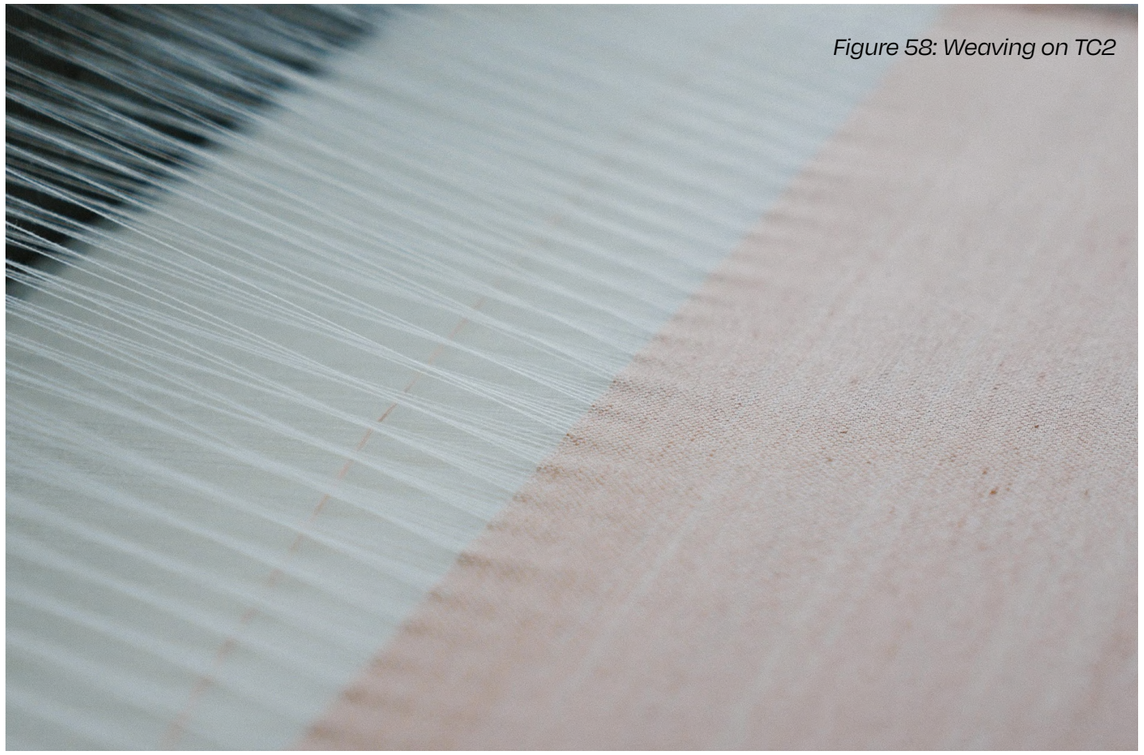


Figure 58: Weaving on TC2



Figure 59: Knitting

5.3. Results & Discussion

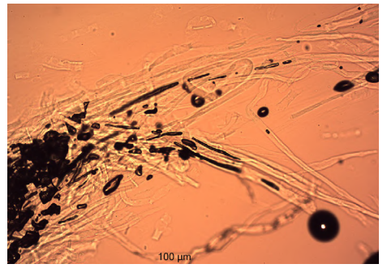
The primary objective of this research was to investigate whether tannins could be incorporated into Ioncell fibres while maintaining a fibre quality comparable to standard Ioncell fibres and simultaneously increasing the hydrophobicity of the resulting fibres, yarns, and fabrics. The following chapter summarises and discusses the results.

5.3.1. Preparation and rheological properties of the spinning dopes

During the preparation of all spinning dopes, both cellulose and tannin dissolved successfully in the ionic liquid (Figures 61.1-61.3), resulting in homogeneous spinning dopes. The incorporation of tannin changed the appearance of the dope from caramel-like to dark red, providing a first visual indication that the tannin had been successfully integrated into the system (Figures 60.1-60.8).

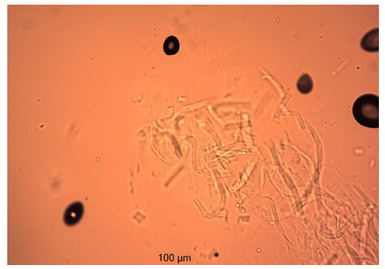
Figures 60.1.-60.8.: Macro- and microscopic images of the dope-making process.





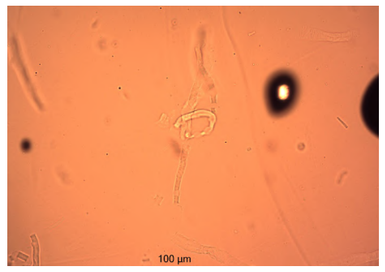
after 30 Minutes





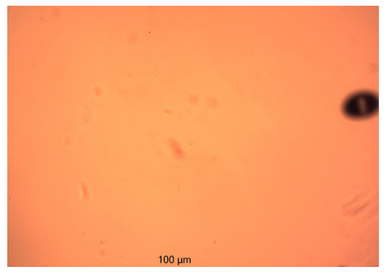
after 60 Minutes



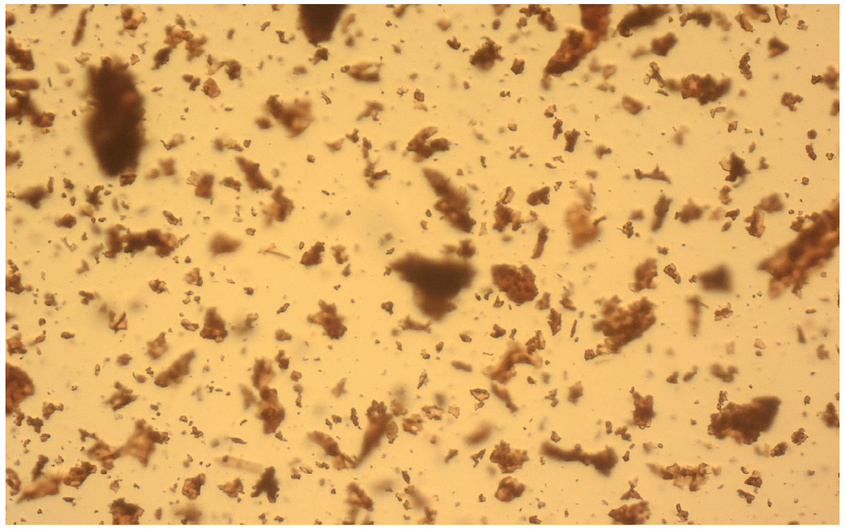


after 90 Minutes

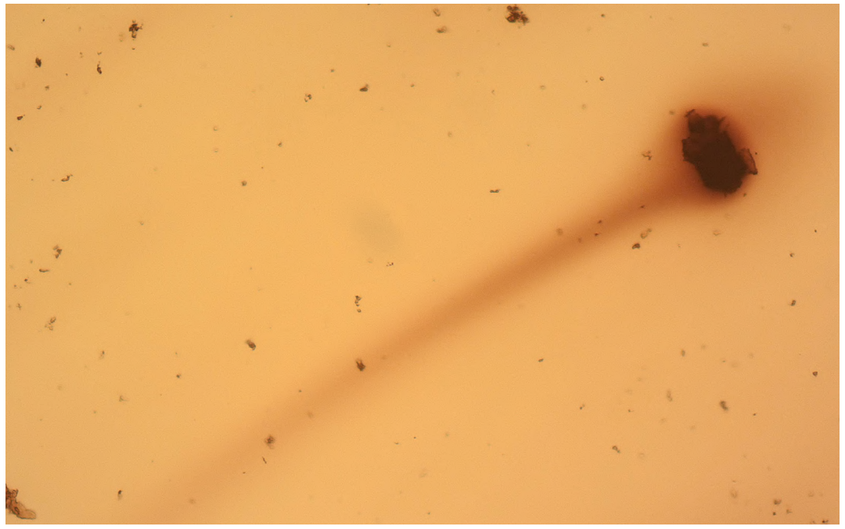




after filtration



Figures 61.1-61.3: Dissolution of tannin in ioniq liquid heating rate: 45°C maximum heat: 85°C



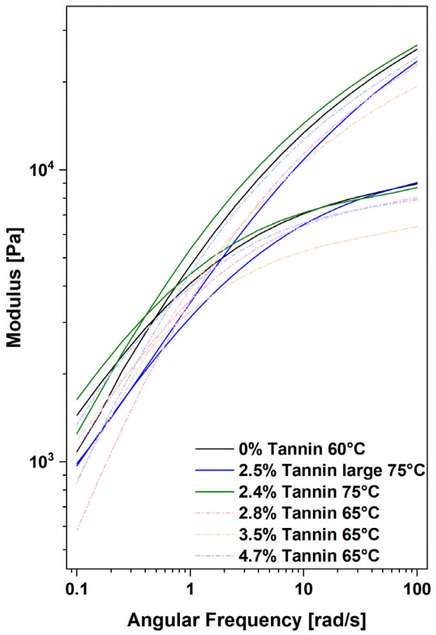
after 2 minutes



after 5 minutes

As shown in Graphs 64 and 65, the rheological measurements indicated that the viscoelastic behaviour of the tannin-containing dopes was comparable to that of the standard Ioncell dope without tannins. This shows that the addition of tannin at the investigated concentrations did not fundamentally alter the rheological behaviour required for fibre spinning. The only exception was Dope 9, which was prepared during the scale-up process. Compared to the laboratory-scale dopes, it exhibited a higher viscosity. This difference is likely related to the larger kneader used during preparation, which enabled more efficient mixing and dissolution of the cellulose, resulting in greater polymer dissolution and, consequently, higher viscosity.

According to Sixta et al. (2015), spinning dopes with a zero-shear viscosity between approximately 25,000 and 35,000 Pa·s generally exhibit good spinnability. This trend was reflected in the spinning experiments (Figure 63). Dope 4 (2.34 wt% tannin) exhibited good spinnability at 60 °C with a zero-shear viscosity of approximately 23,000 Pa*s. Similarly, Dope 9 reached a comparable viscosity of approximately 23,000 Pa*s at 75 °C and could also be spun successfully. The fact that Dope 9 required a substantially higher spinning temperature to reach the same viscosity indicates that its overall viscosity was higher than that of the laboratory-scale dopes. Nevertheless, successful spinning was achieved in both cases, demonstrating that tannin incorporation remained compatible with the Ioncell spinning process.



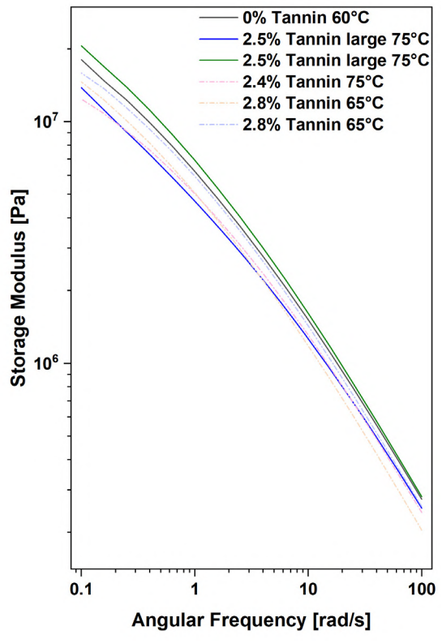


Figure 63: Rheology Summary of Dopes 1-9
Figure 64 & 65: Frequency sweep of Ioncell spinning dopes with varying tannin concentrations.

dope	temperature [°C]	angular frequency [rad/s]	COP [Pa]	zero-shear viscosity [Pa*s]
1: 0% Tannin	60	0.49	3105	2.82E+04
2: 4.67% Tannin	65	0.68	3480	2.33E+04
4&5: 2.35% Tannin	60	0.41	3170	2.30E+04
8: 2.8% Tannin	65	1.02	3593	1.72E+04
7: 3.5% Tannin	65	0.45	2458	2.23E+04
9: 2.5% Tannin	60	0.14	1149	2.34E+04

5.3.2. Spinnability of tannin-containing dopes

The spinning trials demonstrated a clear influence of tannin concentration on the spinnability (Figure 66). Dopes containing between approximately 2.8 and 4.67 wt% tannin could either not be spun successfully or produced highly inconsistent fibres. Fibre breakage occurred repeatedly across different spinning temperatures, indicating that higher tannin concentrations negatively affected the stability of the spinning process (Figure 64). In contrast, dopes containing approximately 2.34 wt% tannin showed excellent spinnability. Dope 4 and Dope 5 enabled continuous fibre collection for approximately 50 minutes at draw ratios of 8 and 11, while a maximum draw ratio of 12.5 was achieved before fibre breakage occurred (Figure 65). According to Asaadi et al the spinnability of the tannin - cellulose fibers can be defined as good (Asaadi et al., 2016).

The successful laboratory-scale formulation was subsequently transferred to a larger spinning setup. The scaled-up Dope 9, containing approximately 2.5 wt% tannin, was successfully spun at 75 °C, yielding approximately 50 g of fibres from an 870 g spinning dope. This demonstrates that the process can be transferred from laboratory to pilot scale while maintaining stable spinning conditions.

Overall, the results indicate that tannin concentrations around 2.5 wt% provide a good balance between successful tannin incorporation and processability, whereas higher tannin concentrations appear to compromise consistent fibre formation.

5.3.3. Tannin retention within the fibre

During the scale-up spinning process and subsequent spin-finish treatment, the processing water gradually turned light brown. This observation suggests that part of the incorporated tannin remained water-soluble and was leached from the fibres during processing. This indicates that the tannin is physically incorporated into the cellulose matrix but is not yet permanently immobilised through chemical bonding. Quantifying the remaining tannin content inside the fibres after spinning and washing should therefore be an important subject of future work. One strategy would be to introduce suitable crosslinking agents that fix the tannins within the cellulose structure (Koopmann et al., 2020). However, any crosslinking approach should be carefully selected to ensure that the recyclability and biodegradability of the Ioncell fibres are not compromised.

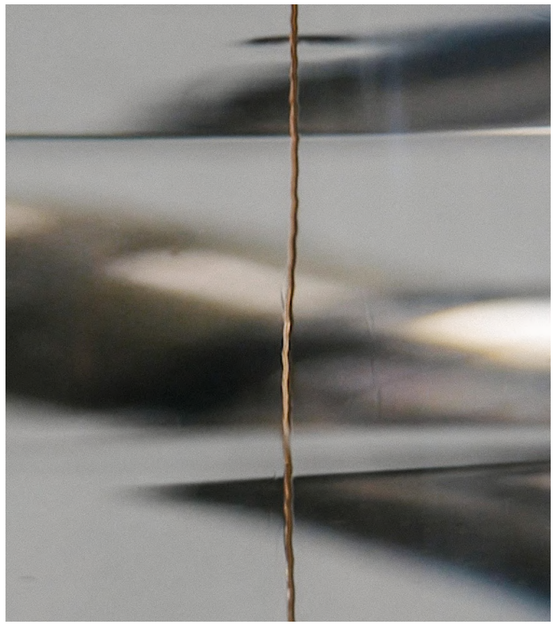


Figure 64: Spinning test dope 2 with 4.67% Tannin



Figure 65: Spinning test dope 4 with 2.35% Tannin

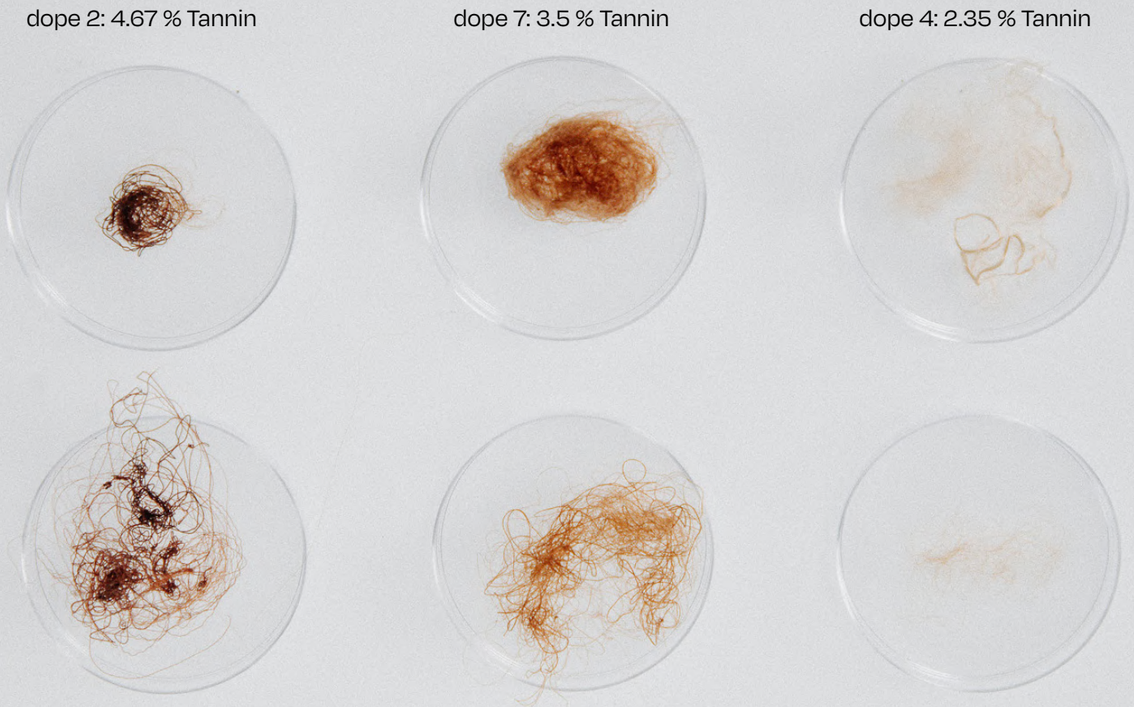


Figure 66: Fibres samples containing different tannin concentrations

5.3.4. Mechanical performance of the fibre

Mechanical testing was performed on standard Ioncell fibres without tannin, laboratory-scale fibres containing 2.34 wt% tannin, and scale-up fibres containing 2.5 wt% tannin. Fibres from each sample were tested at draw ratios of 8 and 11. As Figure 67 and 68 illustrate, the tannin-containing fibres exhibited remarkably consistent mechanical properties, reflected in their low coefficients of variation. This indicates that the spinning process produced fibres of uniform quality despite the incorporation of tannin. The measured linear densities ranged between approximately 1.3 and 1.8 dtex. Although these values are slightly higher than some literature values reported for Ioncell fibres, they remain within the typical range for textile fibres and are therefore suitable for further textile processing. The incorporation of tannin did not negatively affect fibre strength. The measured tenacities ranged from 46 to 51 cN tex^{-1}, demonstrating that high mechanical performance was maintained.

While these values remain below the highest reported Ioncell tenacity of 61.4 cN tex^{-1} (Ma et al., 2020), they nevertheless confirm that the addition of tannin does not substantially compromise the excellent mechanical properties of Ioncell fibres. The elongation at break ranged between approximately 9 and 17%, which is comparable to literature values for standard Ioncell fibres (10.6–14.7%). Variations in elongation can be explained by differences between dry and wet testing conditions, as cellulose fibres generally become more elastic when moisture is present. The scaled-up fibres containing 2.5 wt% tannin exhibited slightly higher elongation at break. However, this difference is more likely attributable to the scale-up spinning process than to the presence of tannin. The fibres were produced using a pilot-scale spinning line equipped with a 300-spinneret spinneret, and differences in spinning and post-processing conditions compared with laboratory-scale monofilament spinning may have influenced the measured elongation.

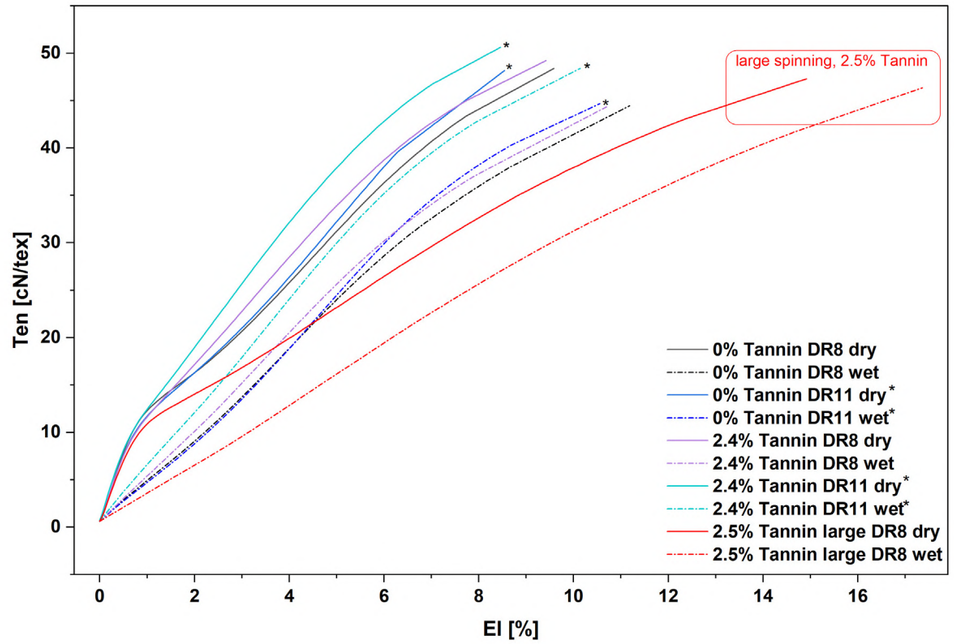


Figure 67: Stress–strain curves of Ioncell fibres with and without tannin under dry and wet conditions.

Sample	El [%]	Ten [cN/tex]	Lin.Den. [dtex]
0% Tannin dry DR 8	10 ± 1	48 ± 4	1.6 ± 0.2
0% Tannin wet DR 8	11 ± 1	45 ± 4	
0% Tannin dry DR 11	9 ± 1	48 ± 4	1.3 ± 0.2
0% Tannin wet DR 11	11 ± 1	45 ± 4	
2.35% Tannin dry DR 8	10 ± 1	49 ± 4	1.5 ± 0.1
2.35% Tannin wet DR 8	11 ± 1	44 ± 5	
2.35% Tannin dry DR 11	9 ± 1	51 ± 5	1.3 ± 0.1
2.35% Tannin wet DR 11	10 ± 1	48 ± 4	
2.5% Tannin dry DR 8	15 ± 2	47 ± 3	1.8± 0.1
2.5% Tannin wet DR 8	17 ± 1	46±3	

Literature Values (Ma et al., 2020)	El [%]	Ten [cN/tex]	Lin.Den. [dtex]
IL-based lyocell from wood pulp	10.6-14.7	49.8-61.4	0.9-1.4

Figure 68: Summary of fibre test results

5.3.5. Mechanical performance of the yarn

The mechanical properties of the spun yarn, summarized in Figure 69, were lower than expected when compared with literature values for standard Ioncell yarns. This finding was somewhat surprising, as both the fibre properties and the yarn-spinning process itself were highly homogeneous.

The discrepancy suggests that factors during yarn spinning or subsequent yarn preparation may have influenced the mechanical performance. Consequently, repeating the yarn spinning and mechanical testing should be considered an important next step to determine whether these results are reproducible or were caused by process-related variability.

Sample	El [%]	Ten [cN/tex]	Lin.Den. [dtex]
2.5% Tannin Yarn (650 Twist, Z)	6.5 ± 3.-1	24 ± 4	24 ± 2

Literature Values (Ma et al., 2020)	El [%]	Ten [cN/tex]	Lin.Den. [dtex]
IL-based lyocell from wood pulp	7.5	33.2	25.5

Figure 69: Summary of yarn test results

5.3.6. Hydrophobic performance

The hydrophobicity measurements represented the key evaluation criterion of this study. As shown in Figures 70.1–70.8, incorporating tannins clearly increased the water resistance of the resulting fabric. The standard Ioncell fabric absorbed a water droplet within approximately two to three seconds. In contrast, the tannin-containing fabric required up to 4 minutes for complete absorption. This substantial difference demonstrates that the incorporation of tannins significantly slowed water uptake. Despite this improvement, the measured contact angle remained below 90°, meaning the material cannot be formally classified as hydrophobic according to the standard definition (Watkins & Dunne, 2021).

Instead, the results indicate that tannin treatment transformed the inherently hydrophilic Ioncell fibres into a considerably more water-resistant material. From a textile perspective, this distinction is important. Many apparel applications do not necessarily require complete water repellency but rather delayed moisture absorption and faster drying behaviour. Therefore, even though the fibres cannot yet be classified as hydrophobic, the observed increase in water resistance represents a highly promising step towards the development of functional bio-based textile fibres.



Figures 70.1.-70.8: Water contact angle test

5.3.7. Summary

Overall, the results demonstrate that tannins can successfully be incorporated into Ioncell fibres while maintaining promising fibre quality and mechanical properties. Although the yarn spinning and mechanical yarn testing yielded lower values than expected and should be repeated to confirm the results, the fibre properties indicate that tannin incorporation does not substantially compromise fibre performance. Furthermore, the hydrophobicity tests showed that adding tannin significantly increased the fibres' water resistance. While the resulting material cannot yet be classified as hydrophobic under the standard definition, the delayed water absorption indicates a clear reduction in the inherent hydrophilicity of Ioncell fibres.

An important finding of the material research is that part of the tannin remains water-soluble. This suggests that tannin is incorporated within the fibre but is not yet permanently immobilised. Therefore, a logical next step will be to investigate suitable crosslinking strategies to improve tannin fixation within the cellulose matrix. Particular attention should be paid to selecting crosslinking agents that preserve the fibres' recyclability and biodegradability, thereby maintaining the sustainable advantages of the Ioncell fibres.

Figure 71: From Ressource to yarn



PART_3

Activities

6

Future applications

The third part of this thesis, Activities, explores potential application fields for the hydrophobic tannin-modified Ioncell fibre. To investigate suitable areas of use, this chapter combines semi-structured expert interviews with market and literature research. The aim to identify promising application contexts, evaluate their technical and commercial relevance, and determine the most appropriate application for the practical design component of this thesis.

Semi-structured interviews were selected because they provide a flexible yet consistent approach to gathering expert knowledge (Semistructured Interview, 2004). While a set of guiding questions was prepared in advance, the order and emphasis of the questions were adapted throughout each interview in response to the participants' expertise and reflections. This allowed emerging topics to be explored beyond the predefined interview guide while making sure that relevant themes were addressed consistently. In total, six semi-structured interviews were conducted with experts from the outdoor apparel, interior textile, and fashion design sectors. To preserve confidentiality, all interviewees have been anonymised, and the findings are presented as synthesised insights rather than attributed to individual participants. The interviews provided useful insights into current material requirements, industry obstacles, and potential fields of application, while also helping to validate preliminary hypotheses regarding the possible product–market fit of the fibre.

The discussion presented in this chapter is deliberately future-oriented. The proposed applications are speculative and refer to a further developed version of the material in which the hydrophobic properties are more pronounced and the tannin component is permanently integrated into the fibre rather than remaining water-soluble. Consequently, the application scenarios should be understood as future opportunities rather than immediate commercial applications. In this sense, the interviews and research served not only to identify possible design spaces but also to determine which performance criteria, industry needs, and contextual aspects would need to be addressed for further development (Niinimäki, 2019).

This perspective is particularly relevant in early-stage material innovation, where technical feasibility alone is insufficient to determine the future potential of a material. Alongside environmental aspects, this thesis therefore draws upon the concepts of Technology Readiness Level (TRL) and Customer Readiness Level (CRL) (Buchner et al., 2019). While the material development presented in this thesis remains at an early TRL stage, progressing from laboratory development to proof of concept, the interviews and market analysis introduce a complementary CRL perspective by examining user needs, industry expectations, and potential market opportunities. Together, these approaches seek to bridge the gap between laboratory-based material development and real-world application, making certain that the fibre is evaluated beyond its technical performance.

Rather than identifying every conceivable application, this chapter aims to identify the most suitable initial application field. Material innovation rarely succeeds by addressing all potential markets simultaneously. Instead, successful commercialisation usually follows a staged market-entry strategy in which a material is first introduced into an application that offers a close alignment among technical capabilities, market demand, manufacturing feasibility, and environmental relevance. This principle is reflected in several contemporary innovations in bio-based materials. For example, Notpla initially focused on seaweed-based coatings for takeaway food packaging before expanding into additional packaging solutions. At the same time, Bolt Threads introduced its mycelium-based material, Mylo, through collaborations with luxury fashion brands before pursuing wider market applications (Texpertise Network, 2025). Following this logic, the purpose of the interviews and subsequent analysis is not only to identify possible applications but also to evaluate which application offers the most coherent entry point for the hydrophobic Ioncell–tannin fibre.

6.1. Potential applications in home textiles

The interviews with interior textile experts indicated that the most promising opportunities for the hydrophobic Ioncell–tannin fibre lie in residential rather than public interior applications. In public interiors, textiles are generally required to fulfil additional performance criteria, particularly fire-retardant properties, which would introduce further technical issues beyond the scope of the present material development. Within residential interiors, regenerated cellulosic fibres such as lyocell were described as particularly attractive for their soft handle and subtle sheen, qualities highly valued in products such as curtains and rugs. These aesthetic characteristics are especially desirable for pile rugs, where wool cannot provide the same level of sheen and silk is increasingly avoided due to concerns regarding animal welfare. Preserving the visual and tactile qualities of regenerated cellulose while introducing hydrophobic functionality could therefore create a material with a unique combination of performance and sensory attributes.

A central limitation of regenerated cellulosic fibres identified by the interviewees is their tendency to water staining. When exposed to moisture, these materials often develop visible marks after drying, reducing their aesthetic quality over time. If hydrophobic modification through tannins can reduce this staining behaviour, the fibre could address an important unmet need within the interior textile sector. Curtains were also identified as a promising application, particularly if improvements in dimensional stability can be achieved. Moisture sensitivity in natural materials often leads to elongation as humidity shifts, which can negatively affect both performance and aesthetics.

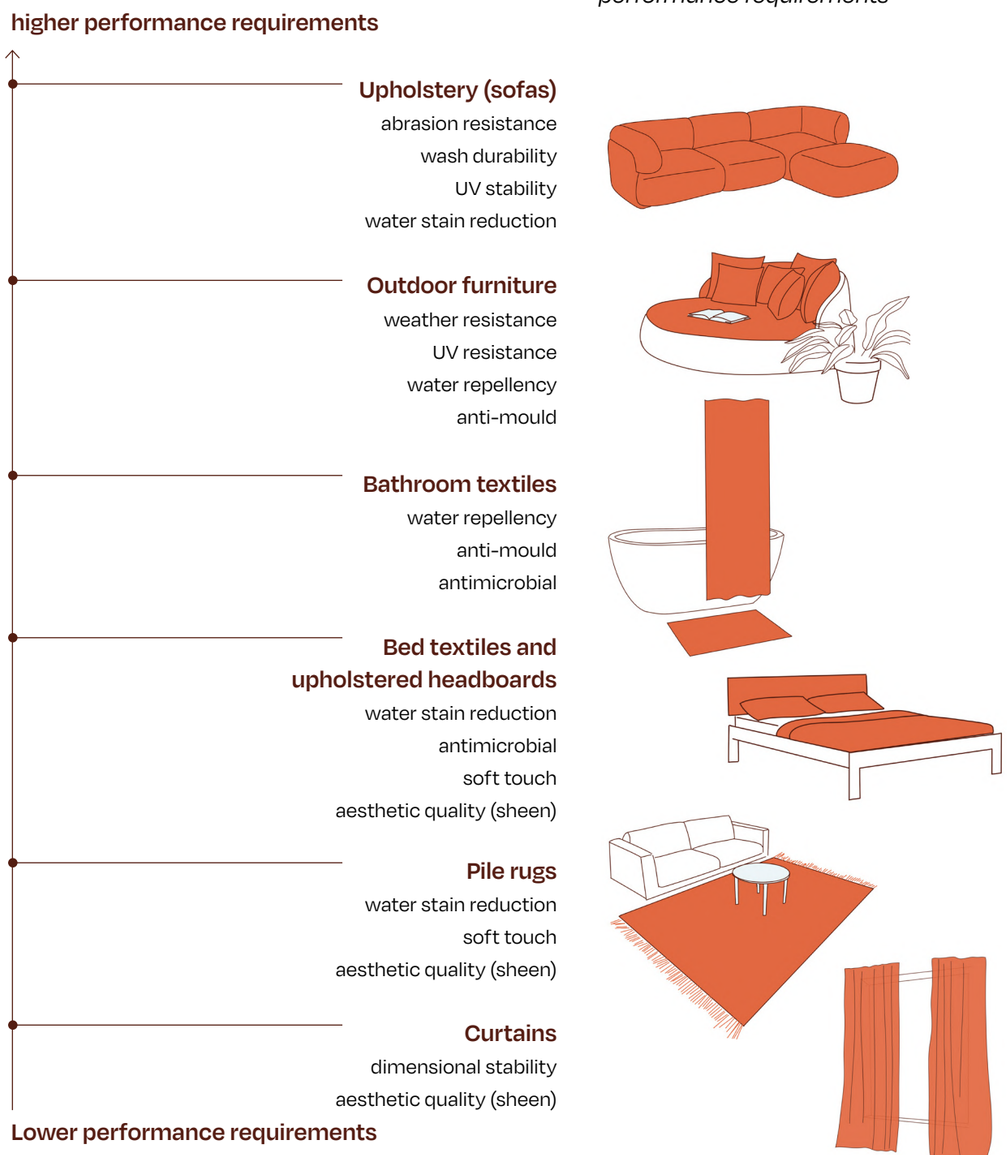
Several additional residential applications emerged during the interviews. Humid environments, such as bathrooms and shower curtains, were considered particularly relevant because water repellency, combined with the potential antimicrobial and anti-mould properties of tannins, could provide clear functional advantages. Outdoor furniture upholstery was also discussed as a promising area, particularly for products used during the summer months when direct skin contact with the textile is common. In this context, a water-repellent material that retains the soft, natural feel of cellulose could offer an attractive alternative to conventional synthetic upholstery fabrics. Similarly, textiles used in close contact with the body, including bed textiles and upholstered headboards, were regarded as suitable applications because consumers generally associate natural materials with greater comfort and well-being.

Despite these opportunities, the interviews also revealed several important challenges. Compared with synthetic fibres such as polyethylene (PE), regenerated cellulosic fibres still have lower abrasion resistance and durability. These properties are particularly critical for upholstery fabrics, which are expected to withstand frequent use, repeated washing, and long product lifetimes. Consequently, any hydrophobic cellulose fibre would need to demonstrate not only water repellency but also mechanical performance comparable to established synthetic alternatives.

The experts further emphasised that interior textiles rarely consist of a single material. Furniture systems typically combine textile covers with petroleum-based foams, adhesives, and structural components, thereby limiting the overall environmental benefits achievable through the textile component alone. This complexity additionally complicates sustainability communication. According to the interviewees, purchasing decisions are still mainly driven by durability, quality, and price. While natural or biodegradable materials are viewed positively, these characteristics are unlikely to compensate for lowered performance or substantially higher costs. Typical upholstery fabrics within the premium segment were reported to be around €20 per metre, whereas prices above approximately €60 per metre were considered difficult to justify for most residential applications.

Another recurring theme concerned the durability of the hydrophobic functionality itself. Unlike conventional surface treatments, which gradually lose their effectiveness through washing and use, the experts emphasised that water repellency should ideally be an intrinsic property of the fibre. Beyond hydrophobicity, the material would need to meet a broader set of performance criteria, including abrasion resistance, wash durability, UV stability, weather resistance, and long-term retention of its haptic and aesthetic qualities. Potential allergenic effects of tannins were also identified as an aspect needing further investigation.

Overall, the interviews suggest that some residential interior textiles represent an attractive long-term application area for the hydrophobic Ioncell–tannin fibre (Figure 72).



The material offers clear opportunities to improve existing regenerated cellulosic textiles by combining their desirable sensory qualities with enhanced water repellency and potential antimicrobial functionality. However, the demanding requirements regarding durability, mechanical performance, and product lifetime indicate that substantial further material development would be required before interior textiles could become a realistic entry market.

Figure 72: Proposed application area for home textiles ranked according to increasing technical performance requirements

6.2. Potential applications in outdoor and activewear apparel

The interviews and literature review show that the applicability of the hydrophobic Ioncell–tannin fibre within the outdoor and activewear sector depends strongly on the specific product category. Generally, outdoor garments have high technical requirements. Waterproof jackets or outdoor trousers are designed for prolonged exposure to rain and therefore rely on multilayer constructions consisting of a synthetic face fabric plus a waterproof membrane or durable water-repellent (DWR) finishes. The performance requirements for those applications regarding waterproofness, abrasion resistance, and long-term durability currently exceed the capabilities of regenerated tannin-cellulosic fibres.

Rather than replacing these high-performance textile systems, the Ioncell–tannin fibre may offer greater potential in use cases requiring moderate water repellency by combining the fibre with a bio-based water-repellent finish, such as a natural wax-based treatment, to create fully bio-based and biodegradable textile systems. Such an approach could extend the material's applicability to products such as lightweight windbreakers, hiking trousers, or garments designed for sporadic exposure to light rain, while physical comfort and environmental performance are prioritised over maximum weather protection.

Nevertheless, these applications would also need considerable improvements in abrasion resistance and long-term durability before the material could compete with established synthetic outdoor textiles. Consequently, while outdoor apparel represents an interesting long-term opportunity, it is currently better understood as a future development pathway than as an immediate entry point for the material.

Compared with outdoor apparel, the research indicated a considerably greater possibility of applications in activewear. In this product category, complete waterproofness is generally less important than efficient moisture management, breathability, drying behaviour, and wearer comfort. These functional requirements more closely align with the existing properties of Ioncell fibres and the anticipated effects of tannin incorporation.

The greatest opportunities were identified in the base and mid layers, where moisture transport and thermal comfort are essential. Within this category, the fibre would compete primarily with merino wool, which is widely valued for its moisture management and odour-reducing properties. A particularly relevant question for future research is whether the tannin-modified fibre could provide comparable performance while avoiding some of the disadvantages associated with merino wool, such as skin irritation experienced by some users.

Beyond sports base layers, low- to medium-impact activewear – including yoga apparel, sports bras, tights, T-shirts, and lightweight trousers – was identified as an interesting application area. These garments function as a second skin and therefore benefit from soft tactile qualities, breathability, efficient moisture transport, and wearer comfort. The anticipated antimicrobial properties of tannins could provide an additional functional advantage by reducing sweat-related odour. One especially promising opportunity concerns moisture-wicking fibre systems. Regenerated cellulosic fibres are currently often blended with synthetic fibres to achieve effective moisture management. Within these blends, the synthetic component contributes hydrophobicity and facilitates capillary-driven moisture transport. A hydrophobic Ioncell–tannin fibre could replace this synthetic component, enabling the development of activewear that maintains functional performance while being entirely bio-based and biodegradable. This possibility is particularly relevant to nylon, which is frequently used in performance apparel because of its hydrophobic properties but is more expensive than polyester.

Despite these opportunities, numerous technical questions remain. Highly elastic garments, such as sports bras or tights, would still require elastane to achieve the necessary stretch and recovery behaviour. This would reduce the circularity of the final textile system and complicate recycling. In addition, abrasion resistance, wash durability, dimensional stability, and long-term mechanical performance are crucial requirements for sportswear, which is subjected to frequent washing and intensive use. According to the interviewees, many emerging bio-based fibres continue to struggle to match the durability of conventional synthetic materials such as polyester or nylon.

Overall, the research indicates that activewear, compared with outdoor apparel, aligns well with the anticipated performance characteristics of the hydrophobic Ioncell–tannin fibre (Figure 73).

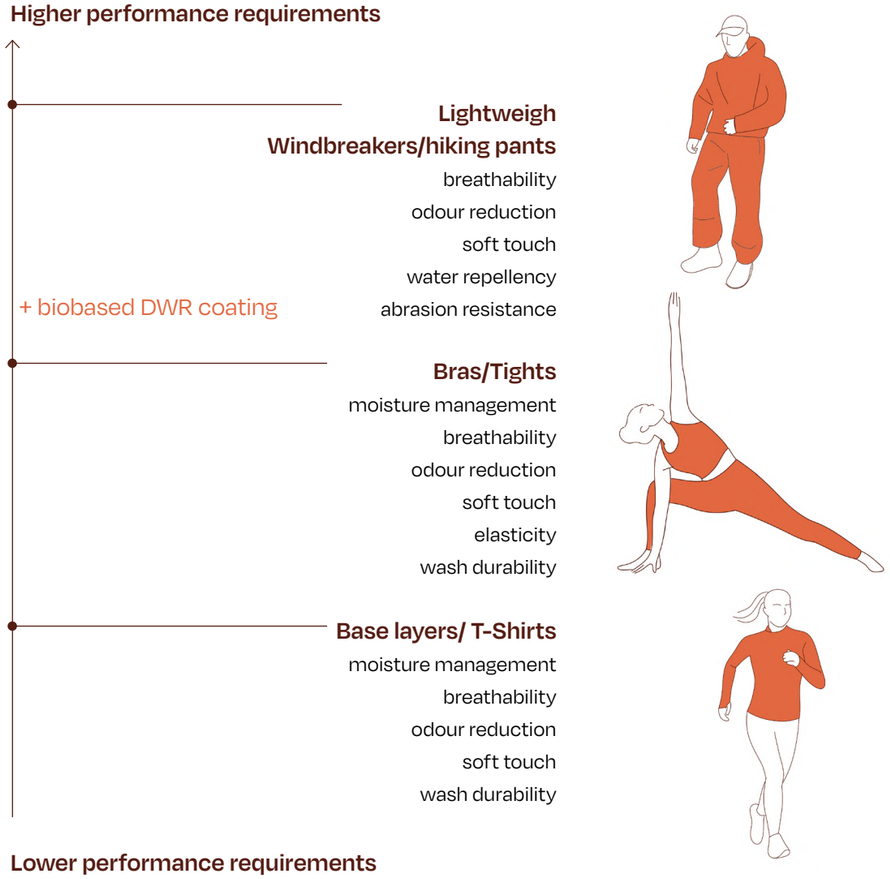


Figure 73: Proposed application area for outdoor and activewear ranked according to increasing technical performance requirements

6.3. Potential applications in footwear

In addition to apparel, one interview partner identified footwear as an interesting application area for the hydrophobic Ioncell–tannin fibre. In particular, knitted shoe uppers were highlighted as an interesting opportunity because they require lightweight, breathable, and comfortable materials while increasingly moving towards bio-based alternatives. Compared with apparel, footwear is also characterised by a strong demand for material innovation, as conventional shoes are typically composed of numerous bonded components that complicate recycling. Athletic shoes are highly complex multi-material systems consisting of synthetic textiles, foams, adhesives, structural support elements, and rubber components, most of which are derived from fossil resources. Furthermore, shoes are exposed to constant abrasion during use, thereby releasing synthetic microplastics into the environment. Developing bio-based alternatives for selected shoe components could therefore help reduce the environmental impact of footwear.

Knitted shoe uppers could be a good component as these structures prioritise breathability, flexibility, and wearer comfort over complete waterproofness (Figure 74). The anticipated softness, moisture management, and potential antimicrobial properties of the hydrophobic Ioncell–tannin fibre could therefore provide useful benefits in this context. At the same time, footwear is among the most mechanically demanding applications for textiles. Shoe uppers must withstand continuous flexing, abrasion, tensile loading, and moisture exposure while maintaining their structural stability. Consequently, abrasion resistance and long-term durability remain critical challenges that would demand substantial further development before the fibre could be considered for footwear applications.

Overall, footwear represents a promising long-term application area for the hydrophobic Ioncell–tannin fibre. However, the demanding mechanical requirements and the complexity of footwear construction suggest that apparel currently provides a more realistic entry point for an emerging material technology.

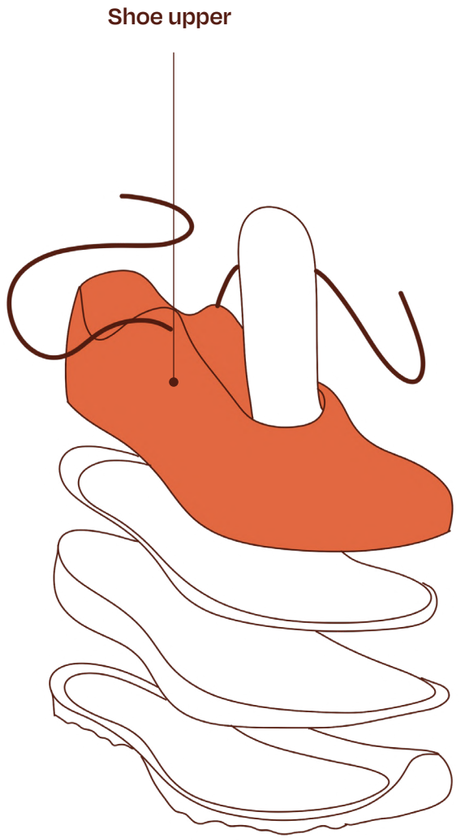


Figure 74: Components of a sports shoe

6.4. Selecting activewear as the initial application field

The comparison of the different application fields demonstrates that the hydrophobic Ioncell–tannin fibre offers potential across a broad range of textile products. Home textiles, outdoor apparel, activewear, and footwear each present opportunities that align with specific material characteristics. At the same time, each sector is associated with distinct technical requirements, meaning that no single application can be regarded as an obvious or universal "low-hanging fruit". Across all fields, the overall weaknesses of regenerated cellulosic fibres are their abrasion resistance, wash durability, and dimensional stability, which have emerged as critical constraints limiting the substitution of existing synthetic fibres.

As discussed in the introduction to this chapter, successful material innovation generally follows a staged market-entry strategy in which a novel material is first introduced into an application where its strengths align most closely with technical requirements, user needs, market demand, and wider societal developments. Building on the preceding analysis, activewear emerged as the application field that provides the strongest overlap among these factors. This decision is informed by a decision matrix adapted from design thinking–based product development frameworks, particularly IDEO's three lenses of innovation, which identify the intersection of desirability, feasibility, and viability as the most promising space for successful innovation (Gonen, 2019). In the context of this thesis, the framework is extended with a fourth lens – ecological sensibility – to integrate environmental aspects into the evaluation process. Together, these four perspectives give a structured justification for selecting the most appropriate initial application field (Figure 75).

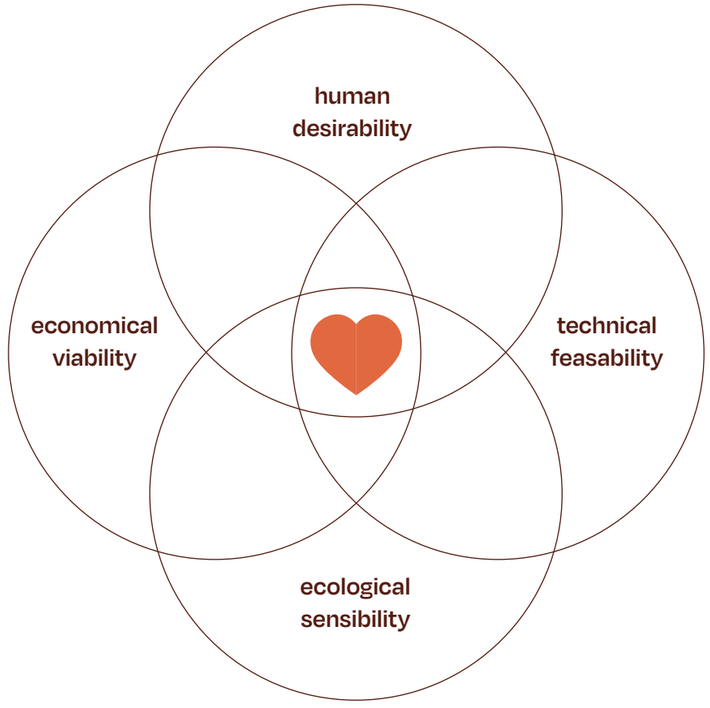


Figure 75: The four lenses of innovation, adopted from IDEO

From a material perspective, activewear aligns particularly well with the anticipated characteristic of the hydrophobic Ioncell–tannin fibre. Activewear products are worn directly against the skin and therefore require softness, breathability, efficient moisture management, and wearer comfort. Standard Ioncell fibres already exhibit favourable characteristics in this regard, including a soft hand feel, silk-like appearance, high breathability, and good moisture absorption (Sixta et al., 2015). The incorporation of tannins has the potential to complement these properties by increasing hydrophobicity, reducing water uptake, accelerating drying behaviour, and introducing antimicrobial functionality that may help reduce sweat-related odour. This combination appears especially relevant for base layers, next-to-skin apparel, and low- to medium-impact activewear, in which comfort and moisture management are important.

Beyond measurable performance characteristics, the material offers distinct experiential qualities that enhance its suitability for activewear. The fibre's copper-toned appearance is central to its material expression (Figure 76). Copper is associated with warmth, comfort, earthiness, and craftsmanship. It also carries historical associations with value and prosperity, as it was the first metal mined and crafted by humans and has long been used in architecture, domestic objects, and currency (Fussell, 2019). In contrast to the cool, bluish-white appearance that characterises many synthetic performance textiles, the warm metallic colour of the hydrophobic Ioncell–tannin fibre evokes a more natural, bodily aesthetic, reflecting its wood-derived origin. This alternative material language supports the development of sportswear that communicates sustainability not only through technical performance but also through its visual and tactile qualities (Figure 77).

This perspective connects with Karana, Pedgley and Rognoli's concept of the "dual language of materials", which argues that materials should be understood through both their measurable technical properties and their experiential qualities (Pedgley et al., 2015). In the context of this thesis, the hydrophobic Ioncell–tannin fibre is therefore evaluated not only through parameters such as hydrophobicity, mechanical performance, abrasion resistance, and durability, but equally through qualities such as softness, comfort, tactility, colour, and the meanings these characteristics communicate to users. As Pedgley et al. (2015) note, design decisions are formed not only by engineering performance but also by designers' and users' sensory perception of materials. Considering both dimensions is therefore essential when evaluating the suitability of a novel fibre for specific applications.



Figure 76: Copper-tone of BarkSkin



Figure 77: Material moodboard copper & BarkSkin

The ecological relevance of activewear further strengthens the choice of this application. Synthetic fibres such as polyester and nylon dominate contemporary sportswear because of their favourable mechanical and moisture-management properties. At the same time, these fibres are among the major contributors to textile-related microplastic pollution. Frequent washing, combined with intensive outdoor use, results in the continuous release of synthetic microfibres into wastewater and the environment. According to the European Environment Agency (2022), textiles account for approximately one-third of primary microplastics entering marine environments. Developing bio-based and biodegradable alternatives that can reduce dependence on fossil-based performance fibres is therefore particularly relevant within this product category.

In addition to its environmental significance, activewear represents an attractive and growing market. The rapid growth of athleisure has transformed sportswear from clothing designed primarily for athletic performance into garments worn in everyday life. As Watkins and Dunne (2021) describe, activewear has become closely associated with health, well-being, comfort, and contemporary lifestyles. This movement has created a growing demand for multifunctional garments that combine technical performance with aesthetics and sustainability. Market analyses also reflect this development: the global sustainable athleisure market was valued at USD 88.75 billion in 2024 and is projected to reach USD 176.05 billion by 2030, driven largely by increasing consumer awareness and demand for environmentally responsible products (Grand View Research, 2024).

At the same time, regulatory developments further support the exploration of bio-based alternatives. Within the European Union, increasing restrictions on PFAS-based water-repellent finishes challenge existing approaches to functional performance textiles and encourage the development of alternative material systems (Doyle et al., 2024).

More broadly, policy initiatives such as the EU Bioeconomy Strategy highlight the role of renewable, bio-based materials in reducing dependence on fossil resources and enhancing the resilience of the textile industry (European Commission, 2025). Consequently, the future regulatory landscape may become increasingly favourable for novel cellulose-based performance fibres.

Finally, activewear offers a particularly compelling narrative context for the speculative design component of this thesis. Few product categories embody such a strong contradiction between intention and material reality. Activewear is widely associated with health, well-being, movement, and conscious lifestyles, yet it is predominantly manufactured from fossil-based synthetic materials that contribute to microplastic pollution and environmental degradation. This tension creates an opportunity to communicate sustainable material innovation through design by making alternative material futures tangible and relatable. Within the design exploration presented in the following chapter, the hydrophobic Ioncell–tannin fibre is therefore referred to as “BarkSkin”, emphasising its function as a protective “second skin” while highlighting its connection to bark and the natural protective strategies that inspired its development.

Taken together, the comparison of application fields demonstrates that activewear provides the strongest overlap between material performance, environmental relevance, market opportunity, and experiential qualities (Figure 78). Although home textiles, outdoor apparel, and footwear remain promising long-term application areas, activewear currently represents the most coherent and strategically suitable entry point for the hydrophobic Ioncell–tannin fibre. Consequently, the speculative design component of this thesis focuses on activewear to explore the material’s future potential from both scientific and design-oriented perspectives.

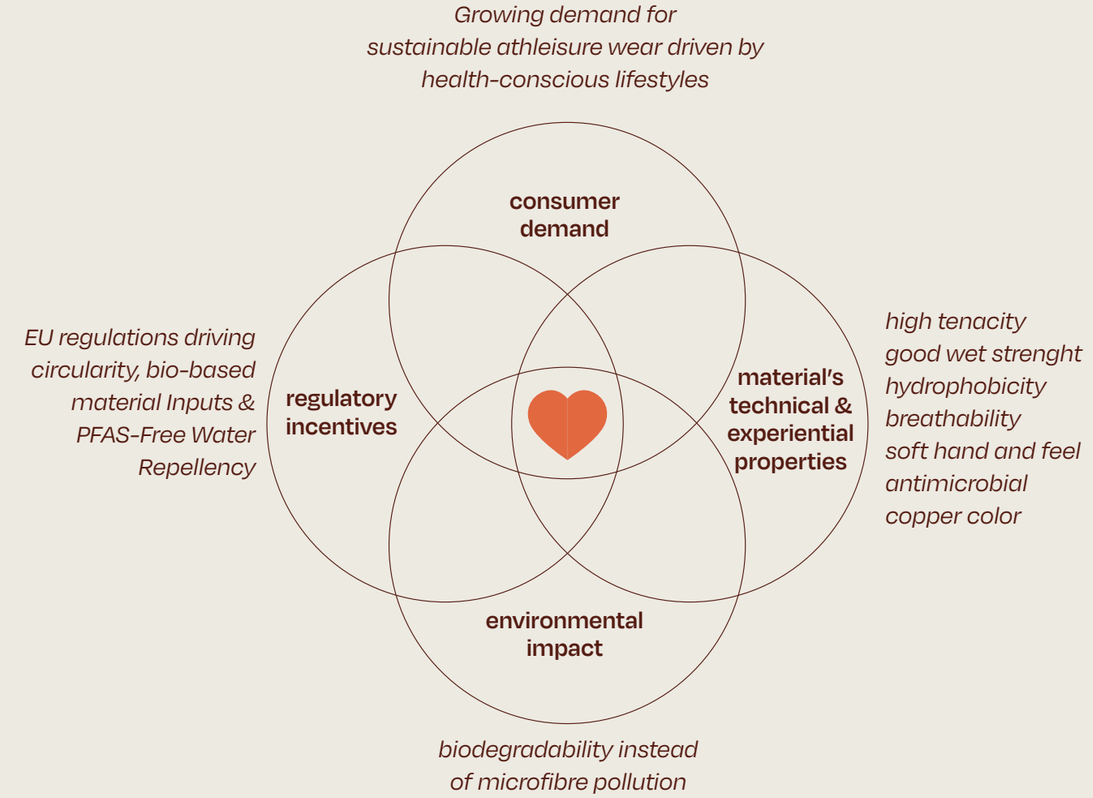


Figure 78: the market opportunity according to the overlap four lenses of innovation for BarkSkin

7

Critical discussion on material innovation

While the previous chapter focused on finding promising application fields for the hydrophobic Ioncell–tannin fibre, one interview partner adopted a wider systemic perspective. Rather than discussing the technical performance or market potential of the material, the interview questioned the role of material innovation itself within the transition towards a more sustainable textile industry. These thoughts go beyond the specific properties of the fibre and raise more fundamental questions concerning consumption, circularity, resource use, and the limits of technological innovation. The following discussion relates these perspectives to existing literature and positions the contribution of this thesis within the wider sustainability debate.

7.1. Material innovation as one part of a systemic transformation

One of the central questions raised during the interview was whether the development of another textile fibre tackles the essential challenges facing the fashion industry. The interview partner argued that, given the existing overproduction of clothing and the increasing global consumption of resources, developing new materials alone cannot solve the environmental crisis. Instead, a sustainable transformation requires questioning current systems of production and consumption rather than simply replacing one material with another.

Closely connected to this discussion is the concept of the rebound effect. As described by Herrmann (2025), improvements in the environmental impact or reductions in the carbon footprint of products and technologies can unintentionally encourage higher levels of production or consumption, thereby neutralizing some or all of the anticipated environmental benefits. Within the textile sector, replacing conventional synthetic fibres with bio-based alternatives therefore does not automatically reduce environmental impacts if overall production volumes continue to increase.

This critique illustrates the broader debate surrounding the limits of the "green growth paradigm", in which scholars argue that efficiency improvements and low-impact technologies often fail to deliver the expected environmental benefits when accompanied by continued economic expansion and rebound effects. Hickel and Kallis (2020), for example, reviewed empirical studies on resource use and carbon emissions and found no evidence that absolute decoupling of economic growth from resource use is achievable globally under sustained growth. They further conclude that absolute decoupling of carbon emissions at the pace required to remain within the 1.5–2 °C climate targets and wider planetary boundaries is highly unlikely. From this perspective, material innovation can be understood as necessary, but not sufficient on its own. Novel fibres such as Ioncell have the potential to reduce environmental impacts and help foster a more regenerative and circular textile economy. However, without parallel changes in production volumes, consumption

patterns, and the economic structures that drive continuous growth, much of this environmental potential might be absorbed by increasing overall production.

In response to these challenges, several economists and sustainability scholars have proposed alternative economic models that explicitly acknowledge planetary boundaries.One influential framework is Raworth's (2012) Doughnut Economics, which argues that economic activity should operate within a "safe and just space for humanity" defined by ecological ceilings and social foundations (Figure 79). Similarly, Herrmann (2025) advocates forms of planned degrowth in high-income economies, in which production and consumption are deliberately reduced to remain within climate and resource limits. Although these approaches differ in their proposed pathways, they share the view that technological innovation alone is insufficient and must be accompanied by limiting overall production.

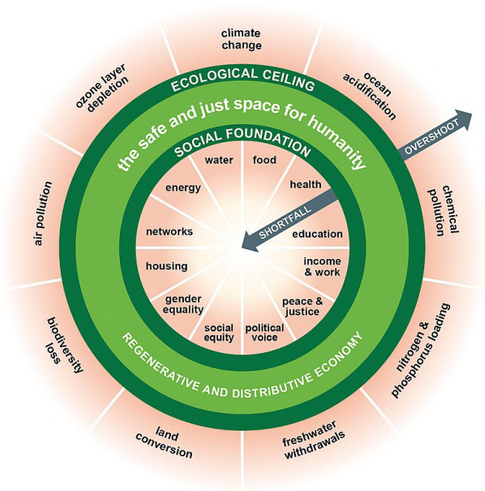


Figure 79: The Doughnut Economy. Source: Doughnut Economics Action Lab.

Such a transition also requires reconsidering the business models that support contemporary production systems. Conventional shareholder-oriented companies are generally structured to maximise financial returns and continuous growth. Alternative ownership and governance models, such as steward-ownership, seek to prioritise a company's long-term mission over short-term profit by legally separating decision-making from capital ownership and restricting profit extraction. In steward-owned companies, profits are primarily reinvested into the organisation or used to further its social or environmental purpose rather than being distributed to external shareholders (Steward-Ownership Community, n.d.). A well-known example is Patagonia, which restructured its ownership so that voting rights are held by a purpose trust while economic rights are transferred to a non-profit organisation, making sure that "all profits, in perpetuity" are dedicated to combating the environmental crisis (Park & Brooks, 2023). Although such examples remain relatively rare, they demonstrate that alternative forms of ownership, production, and value creation are possible and can align business practice more closely with ecological and social objectives.

Consequently, the objective of this thesis is not to justify the development of another textile fibre, nor to suggest that material innovation alone can solve the environmental issues of the textile industry. Instead, it investigates whether, where textile products continue to be required, they can be produced using materials that align more closely with biological cycles and reduce dependence on fossil resources. Within this perspective, BarkSkin should be understood as one possible contribution to a wider systemic transformation that also requires changes in production systems, business models, regulatory frameworks, and patterns of consumption. Furthermore, this thesis argues for a diversification of material inputs in which different bio-based fibres complement one another and are applied according to their respective material properties, rather than replacing all synthetic fibres with a single alternative. Such an approach not only reduces dependence on fossil resources but also helps avoid the overexploitation of individual biomass sources and contributes to a more resilient and regenerative material economy.

7.2. Rethinking the end-of-life narrative

The interview also challenged the frequently used sustainability narrative surrounding biodegradable textiles. While biodegradability is often presented as an environmental advantage, the interview partner questioned its practical relevance in the absence of dedicated infrastructure for compostable textiles. At present, most textile waste is neither composted nor recycled in closed material loops. According to the Expert Network on Textile Recycling (ENTeR, 2015), approximately 73% of textile waste in Europe is currently landfilled or incinerated, while only 13% is recycled. Of this recycled fraction, less than 1% is recycled back into new textile fibres, with the remaining material being downcycled into lower-value products (cascade recycling) (Figure 80). Under the current waste management system, a BarkSkin garment would therefore most likely follow the same disposal pathway as conventional textiles.

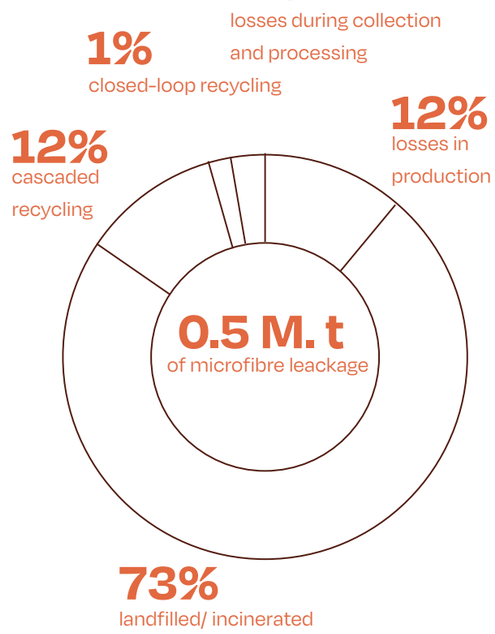


Figure 80: yearly European end-of-life scenarios of clothing adopted from ENTeR

This critique points out an important limitation of depending solely on biodegradability as a sustainability argument. A circular material system needs not only recyclable or biodegradable materials, but also collection, sorting, recycling, or composting infrastructures capable of supporting these end-of-life pathways. From this perspective, biodegradability alone does not guarantee circularity.

Nevertheless, the environmental relevance of biodegradable fibres may go beyond industrial composting. One of the most urgent environmental problems associated with synthetic textiles is the continuous release of persistent microplastic fibres during production, use, washing, and disposal. ENTeR (2015) estimates that approximately 0.5 million tonnes of textile microfibres enter the environment each year. These particles have been detected in marine ecosystems, drinking water, food, and increasingly inside the human body. In this context, the principal environmental benefit of biodegradable fibres may not necessarily lie in enabling composting, but rather in diminishing the long-term accumulation of persistent microfibres within natural ecosystems. Even in cases where textiles ultimately enter landfill or the natural environment, biodegradable fibres have the potential to break down into naturally occurring compounds instead of remaining as persistent plastic pollutants.

In addition, regenerated cellulosic fibres offer the possibility of fibre-to-fibre recycling. Since Ioncell technology has been specifically developed to process recycled cellulose feedstocks while sustaining high fibre quality, future BarkSkin textiles could, in principle, become part of a closed-loop recycling system rather than relying exclusively on biodegradation as their end-of-life strategy. Consequently, compostability should be understood as one of several potential end-of-life pathways rather than the sole sustainability narrative associated with the material.

7.3. Looking beyond biodegradability

The interview further questioned whether regenerated cellulosic fibres should be regarded as equally biodegradable as naturally occurring fibres such as wool or linen. Although Ioncell fibres are man-made, the dissolution and regeneration process does not chemically modify the cellulose molecules themselves. Instead, the cellulose is dissolved in an ionic liquid and subsequently regenerated into a new fibre structure while retaining its original molecular composition. Consequently, regenerated cellulose fibres remain biodegradable in a manner comparable to other cellulosic fibres such as cotton (Moriam et al., 2021). Nevertheless, future chemical modifications of the tannin component, for example, through permanent crosslinking to prevent water solubility, would require testing the biodegradability and recyclability again.

More broadly, the interview pointed out the importance of evaluating new materials through a holistic life-cycle perspective rather than focusing on individual sustainability attributes such as biodegradability or renewable feedstocks. Life-cycle assessments of regenerated cellulosic fibres demonstrate that environmental performance depends on multiple factors, including climate impact, energy demand, water consumption, land use, chemical production, and solvent recovery (Shen & Patel, 2010). While regenerated cellulose fibres generally perform favourably compared with conventional cotton and exhibit a lower environmental impact than fossil-based synthetic fibres, the ecological advantages vary considerably depending on electricity sources, process efficiency, solvent recovery, feedstock selection, and industrial scale. In the case of Ioncell, the closed-loop recovery of the non-toxic ionic liquid and the possibility of producing fibres from recycled textile waste represent important environmental benefits. However, these benefits can only be realised when supported by renewable energy systems and efficient industrial implementation. Accordingly, no textile fibre should be considered inherently sustainable without considering the wider production system in which it is embedded.



Picture 81: tree in UPM forest

7.4. Responsible sourcing of biomass

Another important matter raised during the interview concerns the sourcing of wood, as the raw material for regenerated cellulose fibres. From the interview partner's perspective, forests should mainly serve as carbon sinks and biodiversity reservoirs rather than being harvested for textile production. This concern represents broader discussions about global deforestation. Responsible forest management therefore becomes a key precondition for any expansion of wood-based textile fibres. Certification systems such as FSC and PEFC aim to ensure that forests are managed according to ecological and social criteria, including post-harvest regeneration and the protection of biodiversity. During a visit to UPM's forestry operations in Finland, these principles became visible in practice through continuous replanting programs and the preservation of selected forest areas intended to sustain biodiversity. Although such examples show that sustainable forestry is possible, certification alone cannot eliminate the need for steady monitoring.

At the same time, the current demand for dissolving pulp used in textile production remains relatively small compared with other uses of wood. Man-made cellulosic fibres account for 6–6.5% of the global textile fibre production. That corresponds to 7–7.3 million tonnes of produced textile fibres per year, while the total annual fibre production is close to 100 million tonnes (European Forest Institute, 2024). By contrast, the pulp and paper sector – including paper, tissue and paper-based packaging – is estimated to consume around 33–40% of all industrial wood traded globally, making it by far the larger outlet for wood-derived materials, much of it directed to short-lived or single-use products (World Wildlife Fund, n.d.). In this context, regenerated cellulose fibres currently represent only a minor share of overall wood utilisation, even though their market is growing. Nevertheless, the future expansion of wood-based textile fibres should remain closely tied to responsible biomass sourcing and sustainable forest management to avoid placing additional pressure on natural forests and repeating the mistakes of an extractive mindset.

7.5. Position of this thesis

Taken together, these thoughts emphasise that the sustainability of BarkSkin cannot be evaluated solely through its material composition. It becomes clear that its environmental performance depends on the interaction among renewable raw materials, responsible forestry, renewable energy systems, production efficiency, product lifetime, recycling infrastructure, and broader consumption behaviours. Accordingly, this thesis does not propose BarkSkin as a universal replacement for synthetic fibres or as a stand-alone solution to the environmental challenges of the textile industry.

Instead, it argues for a diversification of material inputs, in which different bio-based fibres coexist and are applied where their individual material properties offer the greatest benefit. In this vision, BarkSkin is not intended to replace all synthetic fibres, but rather to substitute fossil-based materials selectively in applications where its functional properties provide a meaningful advantage.

At the same time, relying on a diversity of bio-based feedstocks can help prevent the overexploitation of any single biomass resource and contribute to a more resilient and regenerative material economy.

Ultimately, however, sustainability cannot be achieved through material innovation alone. Rather, it emerges from the interaction between materials, production systems, business models, policy frameworks, and changing patterns of production and consumption. This perspective aligns with Dunne and Raby's (2013) argument that many of today's environmental and societal challenges cannot be solved solely through technological innovation, but instead require fundamental changes in our values, beliefs, attitudes, and behaviours. In this sense, the purpose of BarkSkin is not simply to propose another material, but to contribute to a broader conversation about how textile materials, production systems, and our relationship with nature have to be reimagined. BarkSkin should therefore be understood not as a final solution, but as one possible contribution towards a wider transformation of the textile industry into systems that operate in closer harmony with ecological cycles.

PART_4

Design & Reflection

8. Designing future material narratives

During the first months of the project, it became increasingly clear that the material development itself would require almost the entire duration of the thesis. Developing the fibre, characterising its properties, and interpreting the experimental results followed a structured scientific roadmap, leaving little room for exploratory design interventions in the laboratory. At the same time, I repeatedly found myself asking what unique contribution I could make as a designer to a project that was already driven by established scientific methods. This question ultimately became the starting point for the practical design component.

Unlike scientific research, which aims to generate knowledge through experimentation and analysis, design has the ability and freedom to make possible futures tangible. Within the field of speculative design, this potential is used to explore probable, plausible, and preferable futures by asking "what if?" questions rather than predicting a single outcome. As Dunne and Raby (2013, p. 6) argue, "by speculating more, at all levels of society, and exploring alternative scenarios, reality will become more malleable." Similarly, they describe speculative design as an invitation for audiences to suspend disbelief, imagine alternative realities, and reflect on how the world could be different (Dunne & Raby, 2013, p. 4). Rather than asking whether the hydrophobic Ioncell–tannin fibre could be produced, which formed the focus of the scientific research, the design component therefore asked a complementary question: What if the material succeeds? How might such a fibre shape future products, material experiences, and relationships between humans and nature? This perspective also aligns with Niinimäki's (2019) understanding of design-driven material innovation (DDMI). Designers contribute to material innovation by imagining future markets, user needs, and broader socio-environmental developments, thereby helping to define the direction of material development beyond technical performance. In interdisciplinary material innovation, designers act as boundary spanners between different fields of expertise. Connecting to the concept of mirroring, Stompff and Smulders (2013, as cited in Niinimäki et al., 2017) describe how designers collect, synthesise, and translate knowledge from different disciplines into sketches, concepts, prototypes, or narratives that diverse audiences can understand. Rather than functioning solely as a communication tool, storytelling and speculative scenario building therefore become design methods through which emerging materials can be interpreted, discussed, and explored.

Initially, I envisioned creating a functional product prototype from the developed fibre. However, after the first month of laboratory work, it became evident that this ambitious objective was unrealistic within the thesis timeframe. Material development proved considerably more time-intensive than anticipated, and the scientific work itself became the primary focus of the project. Rather than interpreting this limitation as a failure, I shifted the design outcome from product design towards communication design. Instead of asking how to design with the material, I asked how the material itself could become the protagonist of the design outcome.

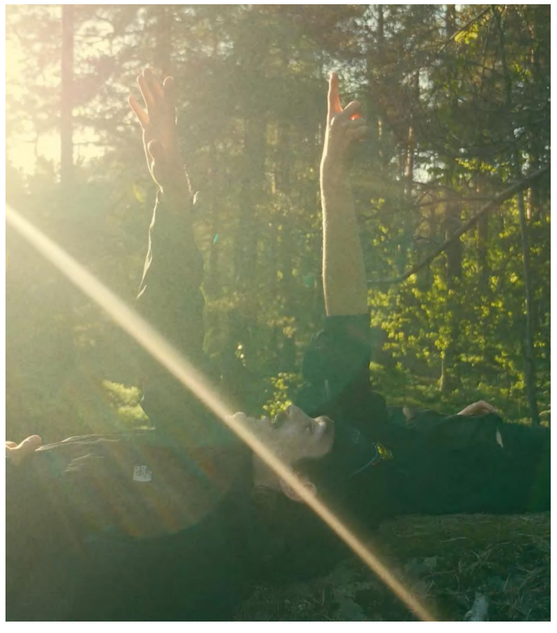
Film emerged as the most appropriate medium for this purpose. Unlike a physical prototype, film can visualise materials, processes, and futures that do not yet exist. It allows microscopic material transformations to be experienced at a human scale, connects scientific knowledge with emotion, and enables future applications to become tangible before they can be realised physically. Storytelling also plays an important role in how knowledge is communicated and remembered. The psychologist Bruner (2020) argues that storytelling represents a fundamental mode of human thought through which people organise experiences and construct meaning. Storytelling, therefore, offers a powerful tool for communicating complex ideas in ways that are meaningful and engaging.

8.1. Translating the research into an immersive installation

The resulting design outcome is an immersive multimedia installation consisting of three interconnected films that follow the conceptual framework developed throughout this thesis: Activism, Actuation, and Activities. Together, these three components communicate not only the research process itself but also the broader environmental motivations and future possibilities of the material (Link to films).

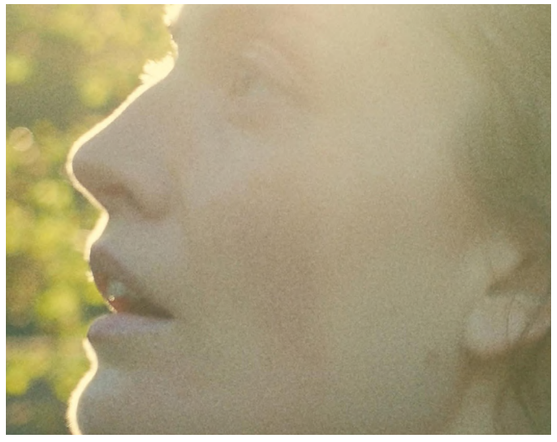
Activism

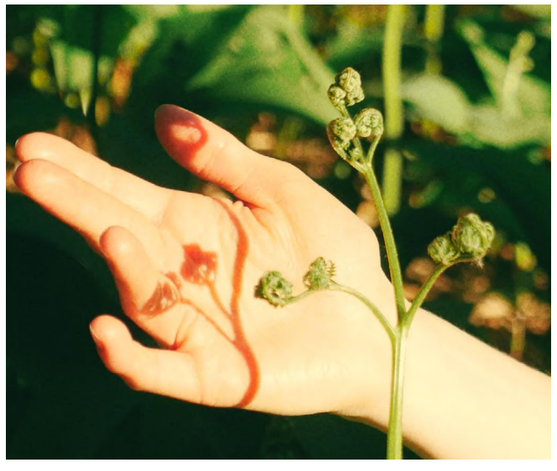
The first film, Activism, establishes the broader context of the project by asking why novel hydrophobic cellulose fibres are needed in the first place. Through atmospheric footage of running in Finnish forests, accompanied by first-person narration, the film reflects on the contradiction of experiencing nature through outdoor sports while simultaneously wearing garments mainly made from fossil-based synthetic materials that contribute to microplastic pollution (Figures 82.1-82.4). Rather than presenting scientific facts alone, the film seeks to establish an emotional connection with the audience. It concludes with the speculative question that initiated the entire project: What if we built textile fibres inspired by bark? In this way, the first film establishes the motivation and the "why" behind the material research.



Figures 82.1-82.4: Stills from "Activism" film



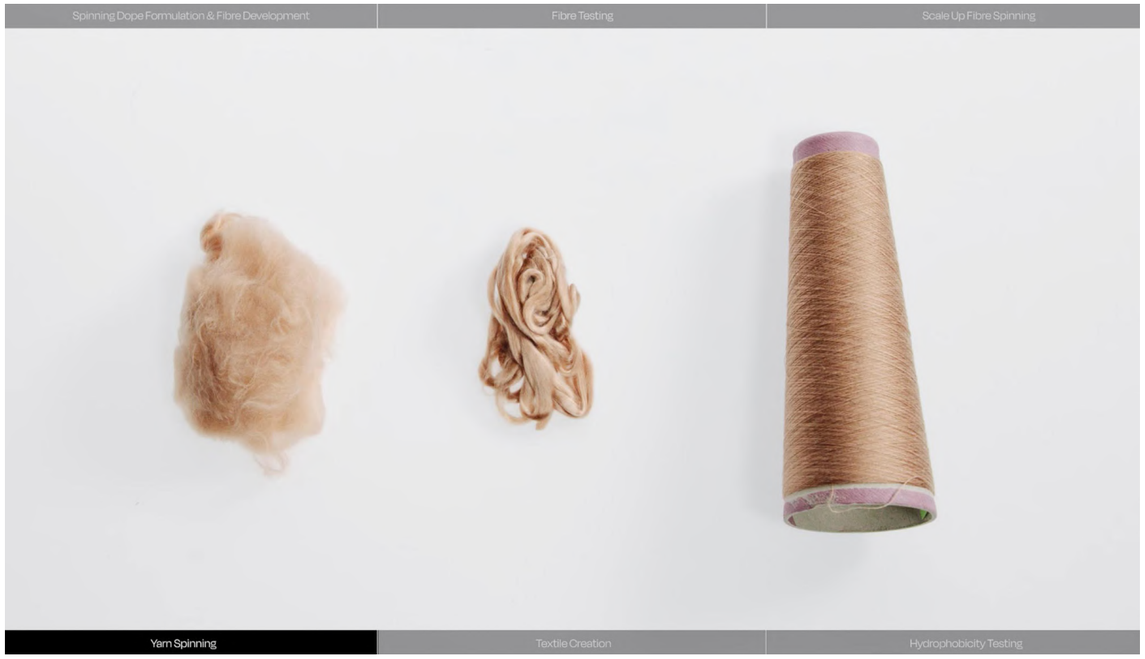


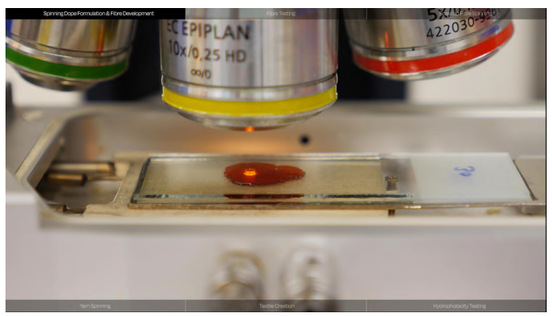


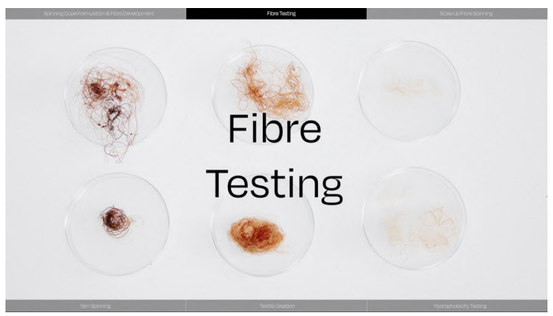
Actuation

The second film, Actuation, translates the scientific research process into a form accessible to audiences outside the laboratory. While material development often remains invisible to the public, the film documents the entire journey from spinning dope preparation to fibre spinning, yarn production, textile manufacturing, and hydrophobicity testing (Figures 83.1-83.2). Throughout the project, the laboratory work was continuously documented through photography and film, thereby making the research process itself part of the final installation.

A visual timeline guides viewers through the different stages of development. At the same time, the accompanying soundtrack is composed of sounds recorded from laboratory equipment, transforming the technical environment into an immersive audiovisual experience. Rather than simply presenting scientific results, the film makes the often invisible processes of material innovation accessible.







Figures 83.1-83.2: Stills from "Actuation" film

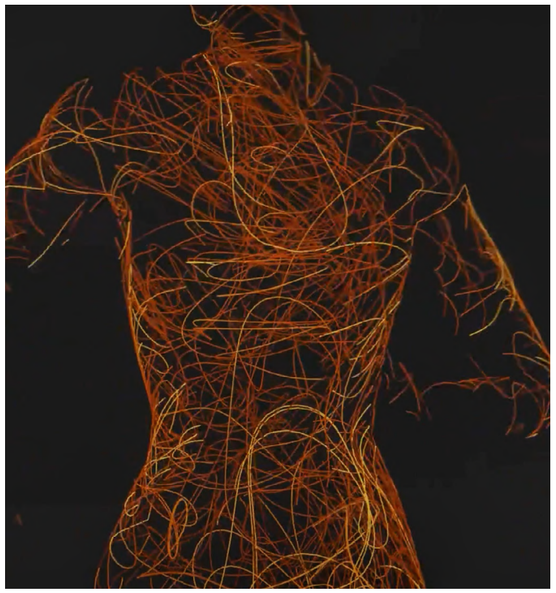
Activities

The third film, Activities, explores possible future applications of the fibre through speculative visualisation. Rather than illustrating a specific product, such as a shoe or garment, the material itself becomes the central protagonist of the narrative. This decision reflects the current stage of material development. While the fibre demonstrates promising application potential, its future performance will depend not only on further optimisation of the fibre itself but also on the ways in which it is processed into textile systems. Properties such as water repellency, moisture management, mechanical performance, and tactile qualities are influenced by multiple levels of textile construction, including yarn spinning, fabric construction (woven, knitted, or nonwoven), fibre blends, and textile finishing.

The speculative animation therefore visualises a human figure composed of BarkSkin fibres performing a choreography inspired by different forms of movement and sport (Figures 84.1-84.3 and 85). The fibres continuously respond to the motion of the body, expressing the close relationship between material and movement. In the final sequence, the figure takes off the garment, which gradually transforms into a tree before returning once again to the human body, symbolising the endless circular relationship between biological resources, materials, use and end of life. The animation was realised in collaboration with two TouchDesigner artists (Julia Zambrzycki and Calvin Suarez), combining computational design, motion and sound into one coherent visual narrative.

Taken together, the installation does not simply communicate the results of the material research. Instead, it extends them by translating scientific knowledge into an accessible, experiential, and emotionally engaging narrative. In this sense, the practical design component functions not only as a form of communication but also as a practice-based method of exploring possible material futures.

Figures 84.1-84.3: Stills from "Activities" film





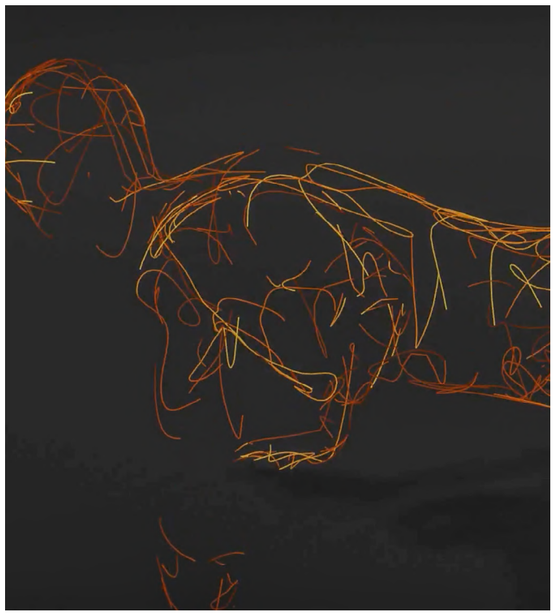
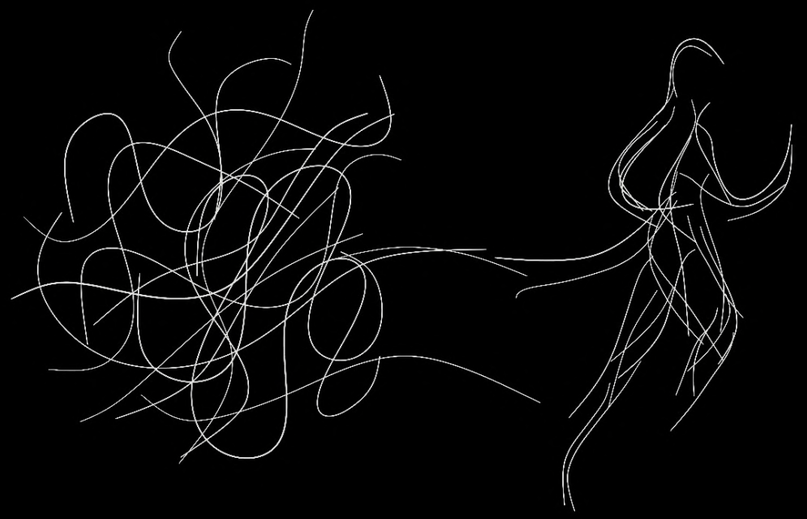


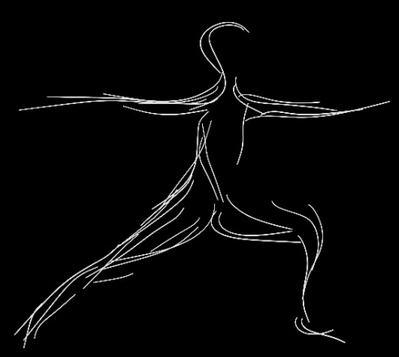
Figure 85: Storyboard of Activities animation



loose fibres turn into the silhouette of a moving body



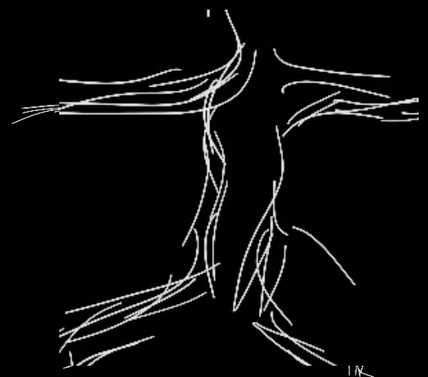
body runs....





close up/ zoom sometimes inbetween











The angle/camera perspective changes from time to time





body takes of cloth and drops it, the fibres dis-perse and grow into a tree





tree turns into fibres & film begins from beginnen (loop)

9. Reflection: Between science and design

Throughout my previous projects and professional work, I have consistently worked at the intersection of design and materials science, holding different positions along the spectrum between the two disciplines.

My journey began as a material designer, exploring bio-based materials through self-directed experimentation in a relatively low-tech environment, where material tinkering – the sensory, hands-on exploration of materials – played a central role. Rognoli and Ayala-Garcia (2021) describe material tinkering as a do-it-yourself approach that enables designers to investigate materials through direct interaction, exploring how they look, feel, sound, smell, and behave. Rather than aiming to optimise technical performance, this exploratory process fosters an embodied understanding of material qualities and their experiential potential.

Over time, this approach evolved towards the emerging role of the designer in the lab, which Pollini (2024) describes as designers who increasingly work within scientific laboratories rather than exclusively in design studios, following experimental protocols, scientific methods, and the rigour of laboratory research. At the same time, my practice aligns with the notion of the biodesigner, who, according to Pollini (2024), develops an understanding of scientific principles to apply nature's potential through transdisciplinary collaboration. While this role similarly bridges science and design, it often engages with biology through experimentation, speculation, and the exploration of possible futures.

Beyond these evolving design roles, I also increasingly found myself acting as an intermediary between scientific research and its practical application – what Stompff and Smulders (2013, as cited in Niinimäki et al., 2017) describe as a boundary spanner: someone who translates knowledge between different disciplines and makes it accessible to diverse stakeholders. This role became particularly evident during my professional work at mujō, where we developed seaweed-based packaging materials and scaled them from laboratory experiments to pilot-scale production. While my co-founder, a materials engineer, primarily served as the interface between mujō and our scientific partners, my role focused on translating the material into potential packaging applications, identifying market opportunities, and engaging with customers through limited-edition products. Although I worked in proximity with the scientists and engineers, the division of roles remained somewhat clear: the engineers were the experts in material development, while I contributed with my skill set as a designer.

This thesis marked a fundamental shift. For the first time, I simultaneously occupied both positions. On the one hand, I worked as a materials engineer, developing the fibre, conducting laboratory experiments according to established scientific protocols, and analysing the resulting data. On the other hand, I assumed the role of a designer, translating the research process and its outcomes into broader societal, environmental, and future-oriented contexts. Rather than feeling like a designer entering the laboratory, I was inhabiting two identities simultaneously: the scientist and the creative designer. As Niinimäki et al. (2017) describe interdisciplinary material innovation, this became a continuous "journey, push and pull between technical and creative dreaming."

During a conversation about the project, Prof. Julia Lohmann described this duality as having "a heart divided into two parts": one half representing the materials engineer, the other the designer, separated by the material itself. I found this metaphor particularly resonant throughout the project. Depending on which role I inhabited, my perspective on the fibre, the research process, and even my understanding of success and failure shifted considerably. The following reflection explores this dual role and the challenges I faced throughout the project, and considers how moving between scientific research and design practice shaped both the project and my understanding of interdisciplinary material innovation.

9.1. Negotiating ownership

The first challenge I had to adapt to was a negotiation of ownership. As a designer, my projects are usually driven by intrinsic motivation. They often begin with a broad curiosity or a personal question that gradually evolves into a concrete concept through research, experimentation, and iteration. Rather than solving a predefined problem, designers continuously frame and reframe both the questions and the direction of a project through what Schön, the inventor of the concept of „reflective practice" (1983), describes as a "reflective conversation with the situation". This iterative process creates a strong sense of ownership, as the project gradually grows out of my own interests, decisions, and creative explorations. This way of working is also closely connected to autonomy. Ryan and Deci (2000) identify autonomy as one of three basic psychological needs that support intrinsic motivation, sustained engagement, and creativity. Although supervisors, collaborators, and external experts regularly contribute valuable feedback throughout a design project, I ultimately decide how this feedback influences the direction of the work.

The structure of the scientific master's thesis is fundamentally different. Rather than emerging from an individual research interest, it is typically embedded within a research group. In my case, the project was part of the Ioncell fibre spinning research group, where researchers, doctoral candidates, and professors collectively investigate different aspects of regenerated cellulose fibre development. The thesis topic „hydrophobising Ioncell fibres with tannins" was therefore not an idea that originated from me but was offered to me by my advisor. Before accepting the project, I spent several days exploring the topic and discussing its scope, scientific relevance, and potential impact with my advisor. While I recognised its potential, I initially struggled to develop the same emotional connection that I usually experience in self-initiated design projects. The feeling of "pouring my heart into a project" was initially absent because the central research question had not emerged from my own curiosity but from the collective goals of the research group. Only gradually did this feeling begin to change.

As the project progressed, and particularly once I started defining my own contribution through the practical design component, I developed a stronger sense of ownership.

A second adjustment concerned decision-making throughout the research process. Unlike my previous design projects, where I largely determined the direction of the work myself, scientific research required close, continuous collaboration with my advisor. We met weekly to discuss experimental results and determine the next steps based on the previous week's outcomes. Major milestones, such as the scale-up spinning trials and yarn production, were planned and conducted together. Rather than designing the research process myself, I was working within an established scientific roadmap and methodological framework. This required me to adapt to a different level of autonomy. Over time, however, I came to appreciate the advantages of this collaborative way of working. The structured guidance provided by an experienced researcher significantly increased the likelihood of meaningful scientific results while allowing me to focus on developing practical laboratory skills rather than first having to establish the entire methodology independently. In retrospect, I realised that the reduced individual freedom was balanced by access to collective expertise and a much deeper scientific understanding than I could have achieved on my own.

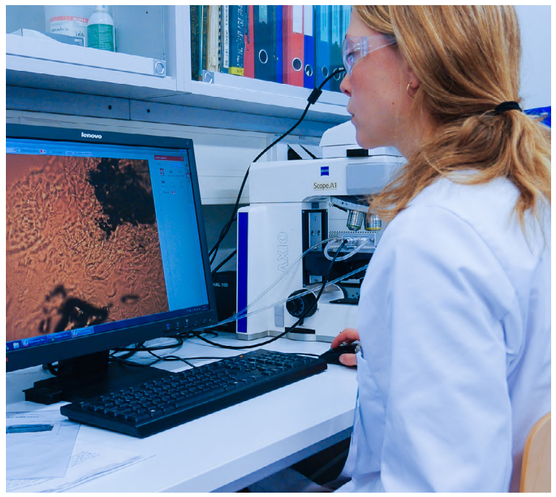


Figure 86: Author analysing the spinning dope.

9.2. Learning to think like a scientist

As Pollini (2024) notes, "despite designers' fascination for science implementation in design processes, acquiring such hybrid skills is not trivial." This observation resonated with my own experience throughout the process. Before I could begin the actual material research, the first month of the project was almost entirely dedicated to laboratory safety training, machine introductions, and learning the scientific methods required to start the material research. I had to familiarise myself with laboratory equipment, fibre spinning machinery, rheological measurements, fibre testing, and a scientific vocabulary that was largely unfamiliar to me. Concepts such as viscoelasticity required repeated revision before I could confidently relate them to the project. Especially during the first month, I felt like an outsider attempting to do the work of an engineer, but considerably less competently than the researchers around me.

During this period, I had several conversations with teachers from ChemArts about my role within the project. I vividly remember Pirjo Kääriäinen asking, "What is the point of doing a chemistry thesis as a designer?" while Anna van der Lei responded to my uncertainty with the remark: "That is why we collaborate." At the time, I repeatedly asked myself what my own contribution as a designer to the project actually was.

Another challenge concerned the fundamentally different attitudes towards uncertainty in science and design. In design, projects are generally directed towards creating a successful outcome. Even when technologies are immature, designers are trained to iterate until a convincing prototype emerges. Scientific research, by contrast, is genuinely open-ended. A failed hypothesis or unsuccessful experiment is not necessarily considered failure but new knowledge. While this distinction appears obvious in retrospect, it was surprisingly difficult for me to work with such uncertainty. During the first weeks, I frequently sought reassurance from my advisor about how likely it was that the approach would work and whether I would be able to produce yarns and textiles. Her answer was simple: "I don't know. You have to find out." At first, this uncertainty felt deeply uncomfortable.

As a designer, I was already thinking ahead to the practical design component and wondering what I would present if the scientific research failed.

This experience also revealed another important difference between scientific and design processes: their pace. As Niinimäki et al. (2017) observe in design-driven material innovation, material development and design development often operate at different tempos. While design concepts can evolve relatively quickly, material innovation progresses through slow, iterative experimentation. This temporal mismatch became particularly apparent during the fibre spinning experiments. Approximately three out of four spinning trials failed. Even when I carefully repeated the same protocol that had worked the previous day, the material often behaved differently. Progress was rarely linear and frequently unpredictable. Yet, over time, frustration gradually gave way to curiosity. As the experiments accumulated, I began to recognise relationships between rheological behaviour, spinning parameters, and fibre quality. When the tannin-modified dope finally became consistently spinnable and the subsequent scale-up to the pilot spinning line proved successful, the sense of achievement was immense – not because every experiment had worked, but because I understood how the different parameters interact.



Figure 87: Author at a spinning trial

Furthermore, I observed some similarities between design and science. While rigorous documentation and experimental procedures were indeed essential, I gradually realised that successful fibre development also depended on gaining an intuitive understanding of the material. I still remember my advisor saying, "You have to find out what the material wants and when it is happy." That sentence immediately reminded me of my previous work with biomaterials, where material development likewise emerged through careful observation, sensory experimentation, and gradually developing an intuitive understanding of the material and its own agency. In this sense, the laboratory work is also very tactile, experiential, and craft-based, requiring the development of embodied material knowledge. As Amy Congdon (2024) similarly reflects, this dimension of material research often remains invisible within scientific publications.

9.3. Rediscovering the role of the designer

The most unexpected challenge of the project was finding it almost impossible to fully inhabit both the scientist and the designer roles simultaneously. While working in the laboratory, I focused entirely on improving the material properties of the fibre. My thinking became increasingly analytical and problem-oriented. As a result, I noticed that I could no longer access the speculative, open-ended mindset that usually characterises my design process.

For a long time, I convinced myself that I first had to develop the "perfect" hydrophobic fibre before I could begin thinking about its future applications. At the same time, the limited timeframe of the thesis required me to make a conscious decision. Instead of waiting until the material was fully optimised, I had to accept that the design component would inevitably engage with uncertainty. This was precisely the moment where speculative design became relevant again. Rather than waiting for a technology to be fully realised, speculative design explores possible futures by asking "What if?" (Dunne & Raby, 2013). Ironically, this had been the underlying methodology of many of my previous research I had temporarily lost sight of it. I realised that I needed physical distance from the laboratory to return to my role as a designer. Therefore, I ended the experimental work to spend almost a month focusing exclusively on the practical design component. This separation allowed me to shift my attention from the question of "how" the fibre functions towards "why" it matters and "what" it could enable in the future.

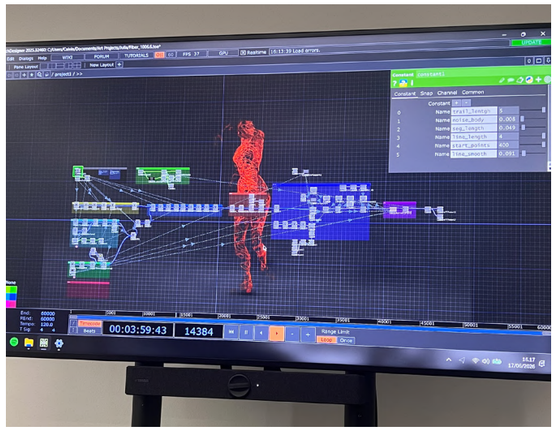


Figure 88: Creating the Animation in TouchDesigner



Figure 89: Recording the water contact angle test

9.4. Concluding reflection

Looking back, this thesis represents one of the steepest learning curves of my education. For the first time, I immersed myself in the scientific end of the spectrum between design and engineering, gaining first-hand experience of the methods, language, and mindset that underpin material development. This experience fundamentally changed my understanding of scientific research and gave me a much deeper appreciation for the patience, precision, and resilience required to develop novel materials. At the same time, it also sharpened my understanding of my own role as a designer. Through both the laboratory work and the investigation of future application scenarios, I know that my contribution does not lie in replacing the expertise of material scientists or engineers, but in complementing it. As the designer I contribute by connecting material innovation with users, applications, markets, and broader societal questions. In this sense, I increasingly see my role as an intermediary between technological development and the contexts in which new materials may ultimately create value.

One of the most rewarding moments of the project was holding a textile in my hands that I produced from the fibres that I had developed in my hands. Experiencing the entire journey – from preparing the spinning dope and producing the fibre to spinning the yarn, knitting the textile, and finally evaluating its properties gave me a holistic understanding of the entire fibre innovation process, an experience that would not have been possible had I remained exclusively in the role of the designer.

Ultimately, my contribution to this project was to complement scientific knowledge with design knowledge. While the material research generated evidence about what the fibre can do, the design process explored why it matters, where it could create value, and how these possibilities can be communicated to broader audiences. Beyond the scientific results presented in this thesis, the practical design component translated laboratory research into an accessible, desirable, and tangible future scenario. In this sense, the project demonstrates that design is not an addition to material innovation but an integral part of shaping how emerging materials are understood, imagined, and ultimately adopted. Science and design represent complementary ways of engaging with the same material. While science seeks to understand and explain the material through systematic experimentation, design explores how to translate the material into meaningful applications, experiences, and future possibilities. It is precisely in the dialogue between these perspectives that interdisciplinary material innovation can unfold. By inhabiting both roles throughout this thesis, I gained not only a deeper understanding of the scientific process but also the ability to communicate more fluently across disciplinary boundaries in future collaborations.





Figure 90: BarkSkin in different processing stages

10

Conclusion

This thesis investigated the potential of tannins to hydrophobise Ioncell fibres and explored their possible applications within the textile sector. In doing so, it presents the first reported investigation of incorporating tannins into regenerated Ioncell fibres. The results show that tannins can be successfully incorporated into the spinning dope, processed into regenerated cellulose fibres, and subsequently spun into yarns without diminishing the mechanical properties of the fibre. While the fibres exhibited mechanical properties comparable to standard Ioncell fibres, the yarns unexpectedly showed lower mechanical performance. As the reasons for this remain unclear, both yarn spinning and mechanical testing should be repeated to clarify the mechanical properties of the yarn. Among the tested formulations, a tannin concentration of 2.5 wt% relative to cellulose showed the most promising overall performance. However, as only a limited number of dope formulations could be investigated within the scope of this thesis, further optimisation may identify even more suitable compositions.

The water contact angle measurements proved that incorporating tannins into the fibre structure increased the water resistance of the resulting textile compared to standard Ioncell fibres. However, the improvement was not sufficient to classify the material as hydrophobic. The experiments further indicated that part of the incorporated tannin remains water-soluble. An important next step is to quantify the remaining tannin content after processing and to investigate suitable crosslinking strategies that immobilise the tannin while preserving the recyclability and biodegradability of the cellulose fibre. Such developments could substantially enhance the hydrophobicity, the long-term functionality and durability of the material.

The second part of the thesis explored potential future application areas for the developed copper-toned fibre, named BarkSkin, inspired by the protective properties of tree bark. Based on their technical, sensory, and visual characteristics, home textiles, as well as outdoor and activewear, were analysed in greater depth. The synthesis of semi-structured interviews with industry experts, together with market and literature research, identified activewear as the most promising application area, offering the strongest overlap between material functionality, environmental relevance, market potential, and user experience. Nevertheless, improving abrasion resistance and long-term durability remains essential before the material can meet the performance requirements of demanding textile applications. Beyond pinpointing promising markets, this application analysis delivers valuable guidance for future material development by highlighting which performance characteristics to prioritise in subsequent research.

The bio-based hydrophobisation approach presented in this thesis contributes to the broader transition from fossil-based synthetic fibres and fluorinated or synthetic durable water-repellent finishes, moving towards renewable and biodegradable functional textile materials that reintegrate into natural cycles. Although the presented material is still in its early stages of development, the work generates new knowledge on integrating functional plant-based compounds directly into regenerated cellulose fibres rather than relying on surface coatings. In doing so, it establishes a basis for future research towards textile materials that combine functional performance with renewable material inputs, circularity, and biodegradability.

Beyond the material development itself, this thesis explored how scientific research can be communicated and contextualised through design. The resulting three-channel video installation translates the thesis's structure into an accessible, experiential narrative, connecting the environmental motivation behind the research, the scientific material development process, and potential future application scenarios. Instead of just communicating scientific findings, the installation demonstrates how speculative design and visual communication can make emerging material innovations tangible for audiences beyond the laboratory. In this way, the design process complements the scientific investigation by exploring not only what the material can do, but also why it matters, where it could create value, and how these possibilities can be communicated to society.

Finally, reflecting on the roles of the designer and the materials engineer throughout this project sheds light on the unique contributions designers can make to interdisciplinary material innovation. While material science provides evidence about what a material is capable of, design helps identify why these capabilities matter, where they may create value, and how future applications can be imagined, questioned, and communicated. Rather than positioning design as the final step following technological development, this thesis highlights the value of involving designers throughout the material innovation process.

Nature has evolved sophisticated protective systems over millions of years that circulate endlessly without relying on persistent synthetic chemicals. By looking to tree bark as a source of inspiration, this thesis proposes a potential direction for future textile fibres that achieve water repellency using solely bio-based materials. Although considerable research is still required before such fibres become commercially viable, I hope that this work contributes, in a small way, to interdisciplinary research at the intersection of material science and design, supporting the development of functional, regenerative, and bio-based textile materials.



Figure 91: Close-Up of wet BarkSkin

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Interviews

Sector	Number of interviews	Interview type
Outdoor and activewear apparel	2	Semi-structured
Interior and home textiles	2	Semi-structured
Fashion and textile design	2	Semi-structured

Pictures

Figure 13 & 14: Biomimicry Institute. (2021). The nature of fashion: Moving towards a regenerative system. https://biomimicry.org/wp-content/uploads/2021/11/The-Nature-of-Fashion_2021.pdf

Figure 22: Gould, J., & Horvath, A. (2023, December 20). The history behind "forever chemicals": How 3M, DuPont and others created PFAS. Manufacturing Dive. https://www.manufacturingdive.com/news/the-history-behind-forever-chemicals-pfas-3m-dupont-pfte-pfoa-pfos/698254/

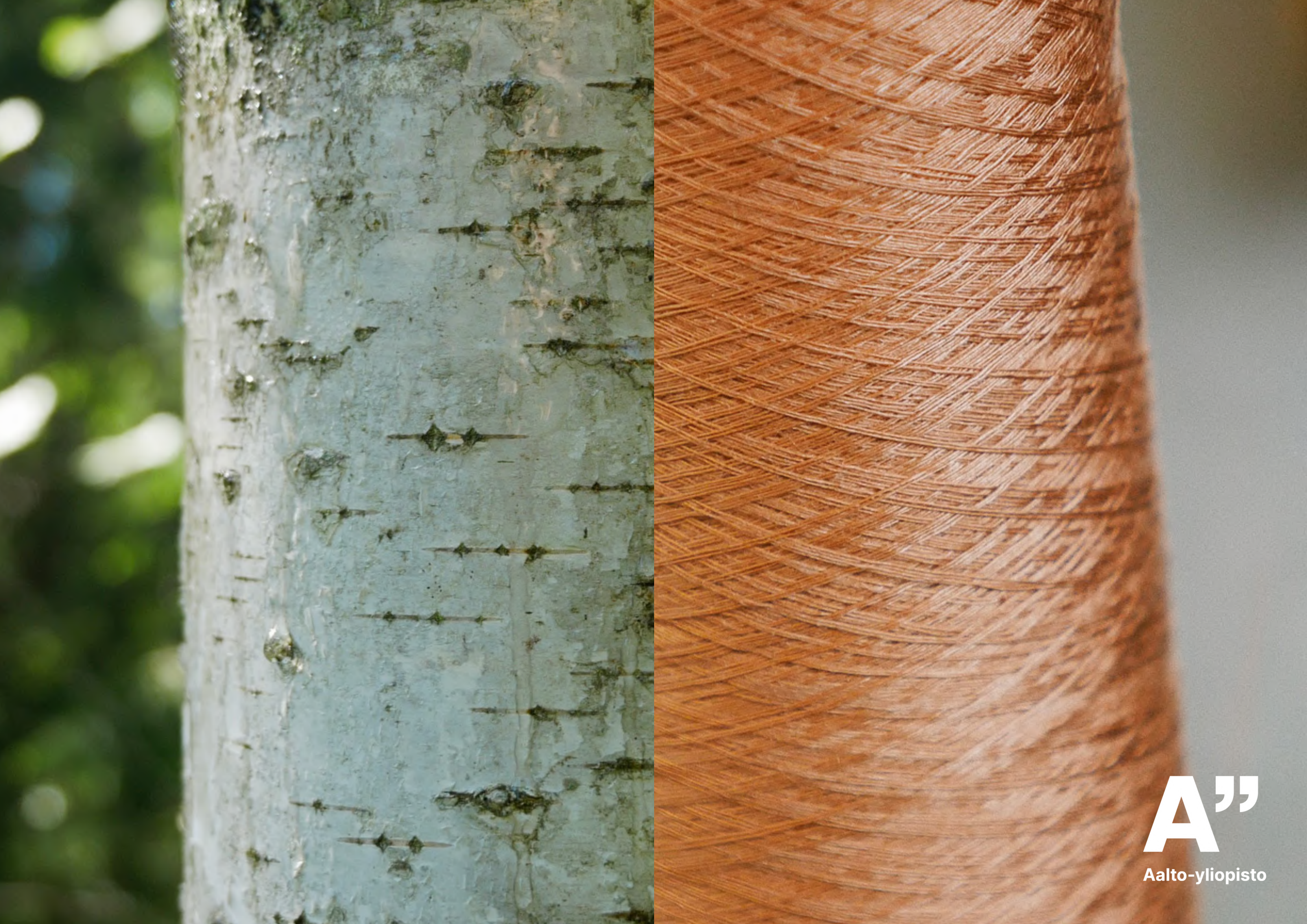
Figure 23: Biomimicry Institute. (2025). Surface allows self-cleaning: Biological strategy. AskNature. https://asknature.org/strategy/surface-allows-self-cleaning/

Figure 27: Nelson Laboratories. (n.d.). Hydrostatic pressure testing. https://www.nelsonlabs.com/testing/hydrostatic-pressure/

Figure 34: Lenzing AG. (n.d.). Filtration of acid bath for cellulosic dope. https://www.lenzing-filtration.com/en/applications/filtration-of-acid-bath-for-cellulosic-dope/

Figure 79: Doughnut Economics Action Lab. (n.d.). About doughnut economics. https://doughnuteconom-ics.org/about-doughnut-economics

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