Sustainable Nonwovens of the Future

- From Research Into Business Opportunities

Tampere University of Applied Sciences

Sustainable Nonwovens of the Future – From Research Into Business Opportunities

Editors: Pia Hautamäki & Noora Raipale
Layout: Kiira Koivunen & Tuomas Korolainen, Mene Creative Oy
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FOREWORD

The nonwovens industry stands out as unique with its versatility and adaptability, which has allowed the industry to explore and innovate new materials, technologies, and applications. In an era where humanity is faced with pressing global challenges such as climate change, and resource scarcity, more sustainable actions are needed. As sustainability can be seen more as a necessity than a preference, more sustainable actions and new sustainable innovations are needed in every sector, including the nonwovens industry. This means innovating for a future where nonwovens not only meet our needs but also contribute positively to our world. This also requires the collective effort of all stakeholders within the nonwovens industry and emphasises the importance of collaboration and partnership in driving sustainable practices.

This practical workbook presents insights from the 2022–2024 SUSTAFIT project in an easily implementable manner. The workbook provides insights into

1. **the market opportunities** that lie ahead when we align business strategies with sustainable practices including exploration of new market opportunities, business models for single-use nonwovens, and segment-specific sustainability strategies;
2. **technical perspectives** on how to manufacture nonwovens in a way that takes sustainability into consideration through novel raw materials, innovations, and technologies, taking into account end-of-life options and up-scaling possibilities with piloting; and
3. **the importance and strategies for building ecosystems** including service and test beds providers, emphasising the collective effort of all stakeholders, the use of digital platforms, and how to create value through ideation. We hope that these practices will be adopted across the broader nonwovens value network, thereby creating substantial impact, and facilitating the emergence of new sustainable businesses.

Nonwovens offer huge opportunities for new kinds of sustainable businesses!

We hope that you will enjoy this workbook. It is designed to give you insights on how to make products in the nonwovens industry more sustainable for the future. We also hope that you will discover valuable information on selecting the right market strategies, including segment-specific strategies, and gain a new understanding of the value network which is critical to operating successfully in the nonwovens industry.

Editors, *Dr. Pia Hautamäki Tampere University of Applied Sciences TAMK* & *M.Sc. Noora Raipale VTT Technical Research Centre of Finland*

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1.

INTRODUCTION

Virpi Rämö** & **Pia Hautamäki

This introductory chapter provides an orientation to our global waste challenge. In this chapter, we also introduce the SUSTAFIT research project effort, undertaken with the support of our funding partner, Business Finland. Take the first steps and learn more about this initiative on our shared path towards sustainable nonwovens.

The Waste Challenge!

The textile industry, including nonwovens, faces global and rapidly growing challenges that necessitate a swift transition to a circular economy. According to the Ellen MacArthur Foundation, less than 1% of clothing is recycled into new textile fibres, highlighting a significant area for improvement (Ellen MacArthur Foundation, 2017). Additionally, the textile industry is a major contributor to environmental concerns, accounting for 10% of global greenhouse gas (GHG) emissions, and 20% of wastewater in the European Union (Ellen MacArthur Foundation, 2017). Amidst these pressing issues, new research and knowledge in the textile circular economy and sustainability play a crucial role in driving the sustainability transformation. On this transformation journey, Finnish innovative companies, showcasing novel fibre innovations, play a central role in transforming new sustainable and circular innovations into new businesses.

The need for change is huge: less than 1% of clothing is recycled into new textile fibres. We need to improve and do better.

The nonwovens industry is known for producing single-use disposable products, such as hygiene products, nappies/diapers, and disposable wipes.

> *We need to transform the production of nonwovens! A study by the EU Commission on the top 10 marine litter items found on European beaches has highlighted the significant presence of nonwoven products. Of the litter found on beaches, approximately 8.1% were wet wipes and around 1.4% feminine hygiene products.*

These findings were instrumental for the introduction of the Single-Use Plastics (SUP) Directive. As a result of the SUP Directive, there has been a concerted push within the nonwovens industry to increasingly focus on the development of sustainable solutions (Directive (EU) 2019/904, 2019).

Did you know that the textile industry is a major contributor to environmental concerns, accounting for 10% of global greenhouse gas (GHG) emissions, and 20% of wastewater in the European Union? (Source: European Parliament, 2023)

What Are Nonwovens?

Nonwovens represent a unique category within the textile industry, distinguished by their method of production and structural characteristics. EDANA, a leading global association of the nonwovens and related industries defines a nonwoven as *"an engineered fibrous assembly, primarily planar, which has been given a designed level of structural integrity by physical and/or chemical means, excluding weaving, knitting or paper making"* (EDANA, 2024). In simpler terms, nonwovens are versatile fabric materials composed of fibres that are bonded together to form a flat structure. Unlike traditional textiles, they are not produced by knitting or weaving. Instead, the fibres are combined through various processes that may include entangling with needles, bonding with adhesive, or fusing the fibres together with heat or pressure.

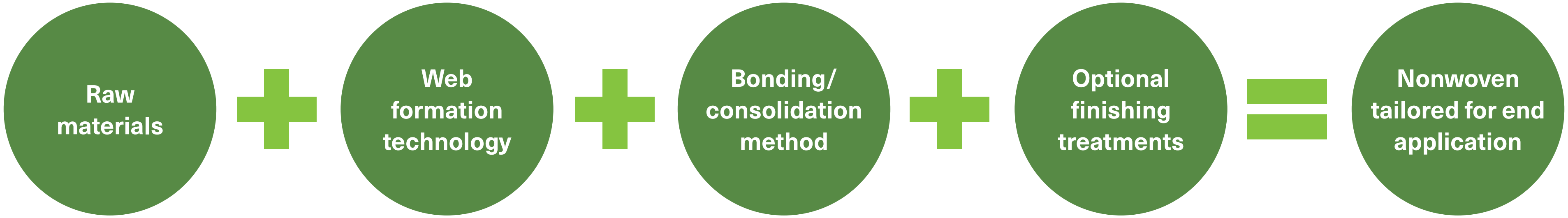


Figure 1. Simplified process steps of nonwoven production (Source: Own elaboration)

This manufacturing difference leads to a distinct set of properties for nonwovens. They can be designed for specific functions and tailored to meet the demands of different consumer and industrial applications. The flexibility in their production process allows for a broad range of characteristics, from soft and cloth-like to strong and resilient. This versatility is what makes nonwovens so popular in numerous sectors, including in the manufacturing of medical, automotive, and hygiene products.

All of us see and use nonwovens in our daily lives. Figure 2 below shows that nonwovens are used in various industries: in absorbent hygiene products, in agriculture and horticulture, in automotive and transportation, in clothing and footwear, in construction and building, in electrics and electronics, in filtration, in food and beverage, in geotextiles and civil engineering, in the household, in medical, in packaging, in protective clothing, and in different wipes.

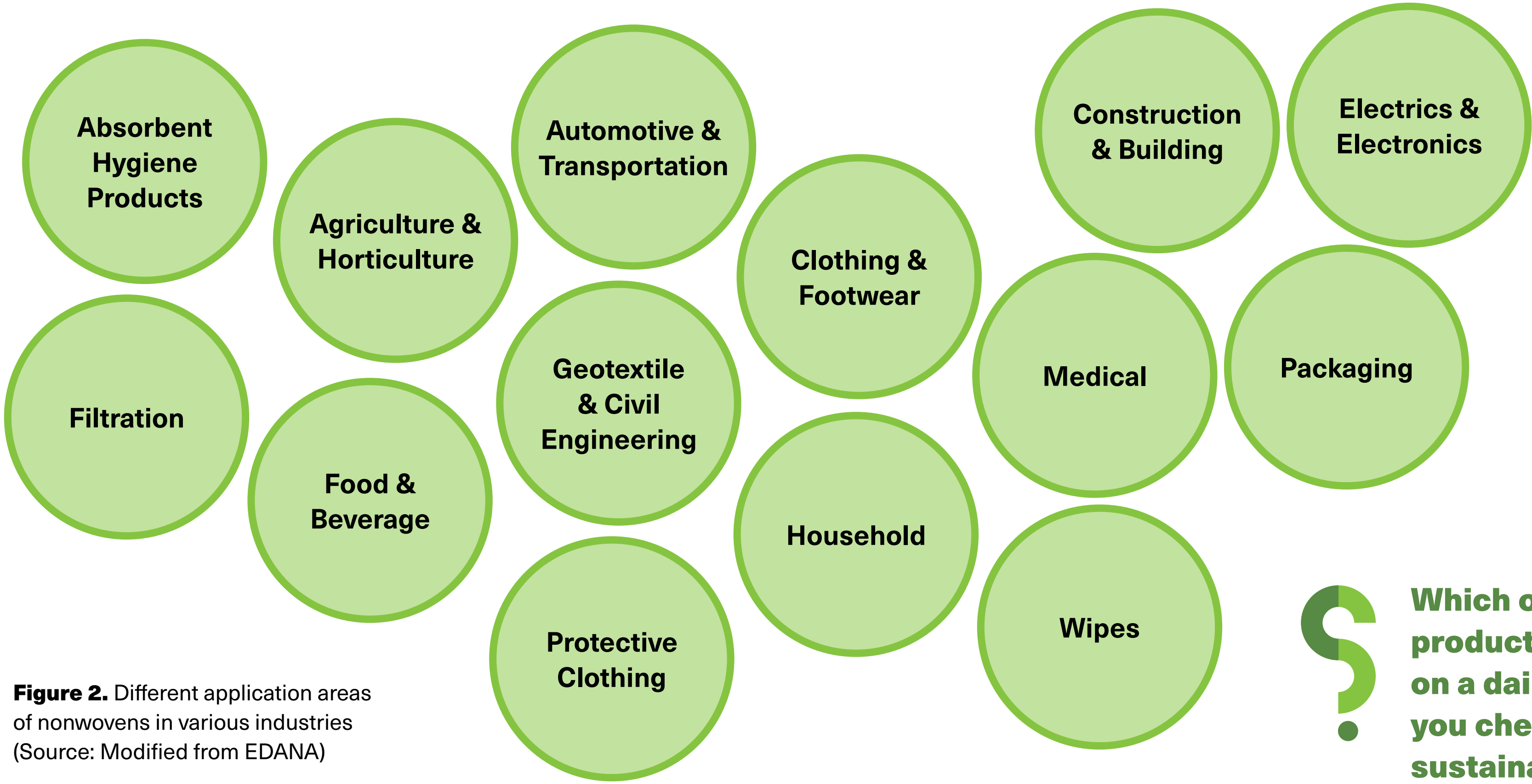


Figure 2. Different application areas of nonwovens in various industries (Source: Modified from EDANA)

Which of these products do you use on a daily basis? Do you check a product's sustainability markings before you buy it?

Introduction to the SUSTAFIT Research Project

The SUSTAFIT project focused on sustainable, fit-for-purpose nonwovens, and it was established in response to the Finnish industry's need to enhance its competitiveness and expand its opportunities in the varied and growing market for sustainable nonwovens. To achieve this, industry representatives emphasise the importance of strengthening the collaborative network among stakeholders, including businesses, research institutions, service providers, and customers. This collaborative approach is essential for fostering sustainable business practices in the nonwovens sector.

In response to this need, the SUSTAFIT research project outlined sustainability strategies for specific application segments, and facilitated a deeper understanding of the knowledge gaps identified collaboratively. The gaps identified relate to the expansion of sustainable raw materials in nonwovens and the correlations between raw material, processing, and properties. A particular focus of SUSTAFIT was to enhance the appeal of sustainable fibres for nonwoven applications. This was achieved by improving their hydrophobicity and antimicrobial properties, addressing two significant barriers to the broader adoption of sustainable fibres.

Methodologically, the SUSTAFIT research project functioned as an innovation ecosystem that facilitated the development of new material innovations. This was achieved by advancing from laboratory scale to pilot scale, leveraging raw materials, knowledge, and infrastructure from various participating entities. The project also engaged stakeholders in collaborative workshops to foster innovation and address the research gaps identified. Additionally, it effectively incorporated stakeholders and resources beyond the consortium into the knowledge creation process in various ways.

Sustafit partners

SUSTAFIT – Sustainable fit-for-purpose nonwovens was a research project funded by Business Finland conducted between 1 October 2022 and 30 September 2024. The research was carried out by Tampere University of Applied Sciences (project coordinator), VTT Technical Research Centre of Finland and Aalto University. In addition, participants included seventeen industry companies in the nonwoven value network: Fortum, UPM, Sulzer, Kemira, Lounais-Suomen Jätehuolto, Anpap, Spinnova, Nordic Bioproducts Group, Rester, Valmet, SharpCell, NordShield, Fiber-X, JedX Medcare, Paptic, Mirka, and Lixea.

SUSTAFIT – Sustainable fit-for-purpose nonwovens responded to the Finnish industry's need to boost competitiveness and broaden opportunities in the versatile, growing sustainable nonwoven markets.

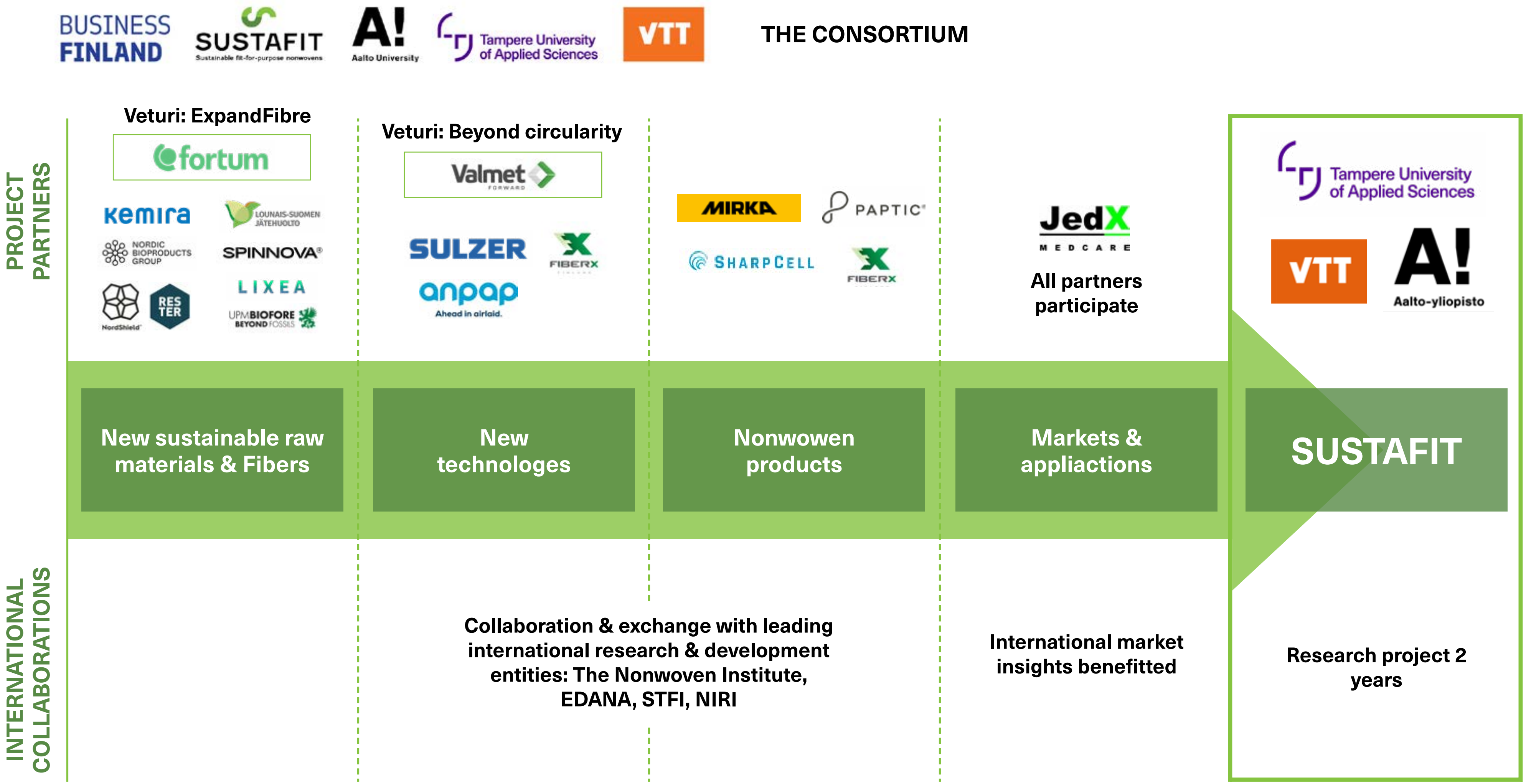
SUSTAFIT described application segment specific sustainability strategies. The project also built understanding on the jointly identified knowledge gaps around how to expand the use of sustainable and recycled fibres from alternative renewable and sustainable feedstocks in nonwovens, and how to relate the properties of the raw materials and their processing to the properties of the nonwoven products. As one specific target, SUSTAFIT boosted the attractiveness of sustainable fibres for nonwoven applications by developing their hydrophobicity and antimicrobial performance, the two major restricting factors for increased sustainable fibre introduction. SUSTAFIT tackled these jointly identified research gaps through practical demonstrations and by involving stakeholders to jointly assess new value chain opportunities.

SUSTAFIT aimed to

- describe **segment-specific sustainability strategies** for nonwoven application areas (addressed in the SUSTAFIT work package 1);
- **broaden the feedstock portfolio** for sustainable nonwovens (addressed in the SUSTAFIT work package 2);
- create **understanding between the properties** of raw materials, processing, and nonwoven **products** (addressed in the SUSTAFIT work package 2);
- develop **water-repellent** and **antimicrobial** bio-based nonwovens (addressed in the SUSTAFIT work package 3);
- identify **business opportunities** for sustainable and high-performance nonwovens (addressed in the SUSTAFIT work package 3); and
- **increase international collaboration** and disseminate the outcomes (addressed in the SUSTAFIT work package 4).

If you are interested in learning more about what we have been working on in the SUSTAFIT research project beyond what is presented in this Practical Workbook, please visit our webpage: https://projects.tuni.fi/sustafit

Figure 3. The SUSTAFIT project consortium (Source: SUSTAFIT)



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2.

MARKET OPPORTUNITIES

The second section of the workbook, Market Opportunities, addresses the opportunities that the nonwovens industry offers for new players aiming to support the sustainability transformation within the sector. We also showcase how regulations are driving the industry to renew its operations, and map out the various players in the sector. Furthermore, we provide examples of business models and strategies for selecting segment-specific sustainability approaches.

2.1 New Market Opportunities

Shruti Dharwadkar** & **Pia Hautamäki

In this chapter we briefly explore the current nonwovens landscape, and introduce potential market openings for businesses and their partners. This is for you if you are interested to learn more about the current status of the nonwovens industry, and what kinds of potential market opportunities it could open up.

The global nonwovens industry has undergone remarkable growth, fuelled by technological advancements and evolving consumer preferences. Nonwoven fabrics, known for their versatility and cost-effectiveness, have found applications across diverse industries, presenting a plethora of market opportunities. A significant driver of market optimism is the expansive growth of the global textile industry, a pivotal factor contributing to overall market expansion (Global Nonwoven Fabrics Market Report, 2022). The Asia-Pacific region, functioning as a global manufacturing hub, particularly exemplified by India and China, boasts robust infrastructure capable of meeting various industry needs. Geographically, Asia-Pacific emerges as the largest consumer of nonwoven fabrics, strategically establishing its dominance and leveraging key factors for market leadership (Chemanalyst, 2023).

According to Innovation in Textiles (2022), in 2021, China emerged as the leading nonwoven fabric producer in Asia, with increased production compared to the preceding year. India and Indonesia also experienced growth in nonwoven fabric production. Despite a modest overall increase in Asia's nonwoven fabric production in 2021, following a significant surge in 2020 and consistent growth from 2010 to 2019, the industry is anticipated to sustain a robust growth trajectory in the future. (Innovation in Textiles, 2022.)

Asian countries are emerging as the biggest players in the production of nonwoven materials.

Looking ahead, nonwoven fabrics, particularly in healthcare applications, are poised to dominate the market, with China leading as the largest market (Research & Markets, 2022). However, India is expected to exhibit the fastest growth, driven by escalating demand from the healthcare and textile industries. The polyester market is predicted to experience substantial demand, driven by the growing concentration of trade in Asia, particularly in textile and apparel products. (Dharwadkar & Hautamäki, 2023). A significant factor propelling the nonwoven fabric market in the Asia-Pacific region is the increasing demand for both baby and adult nappies/diapers. While there was initial reluctance in the region to adopt adult nappies/diapers, influences from western countries have led to a significant surge in usage. This trend is further propelled by the rising average age of the population in these countries. The availability of a cost-effective and abundant labour force in the Asia-Pacific region, compared to North America and Europe, facilitates an efficient and economical production process. (Research & Markets, 2022). However, consumer preferences in the Asia-Pacific region diverge from Europe and America, where sustainability holds greater importance, primarily due to regulatory considerations. In Asia-Pacific, functionality takes precedence over sustainability, with sustainability viewed as desirable but non-essential. This regional contrast underscores the importance of understanding diverse market dynamics (Velocel, 2023).

Benefits for the Industry

A wide range of companies can benefit from this dynamic landscape of the global nonwovens industry.

Access to growing markets

1) The growing need for nonwovens will provide companies with access to growing markets, particularly in the Asia-Pacific region, where nonwoven fabric consumption is dominant. A strategic positioning as contributors to sustainability within the nonwovens sector enhances a company's brand image, appealing to the growing demographic of environmentally conscious consumers.

Leading positions still available

2) When a company focuses on innovation in sustainable practices, they will be able to actively participate in research and development initiatives, fostering creativity in eco-friendly products. By aligning with sustainability targets, the company can establish themselves as leaders in providing environmentally friendly nonwoven solutions, gaining a competitive advantage in a market where sustainability is becoming a key consideration.

Possibility to play a significant role in new market dynamics

3) Forecasted trends, such as the prominence of nonwoven fabrics in healthcare applications and the rising demand for nappies/diapers, present strategic opportunities for companies to adapt their product offerings to align with these market dynamics.

Share of the B2B field in sustainability marketing

4) Harnessing the power of sustainability marketing is not merely an operational tactic but a catalyst for innovation and transformation. The essence of successful sustainability marketing is built on critical principles highlighted by Lunde (2018), including credibility, trust, transparency, consistency, education, and engaging stakeholders. These core values not only improve the impact of marketing efforts but also foster a sense of authenticity and dependability, qualities crucial for standing out in the current competitive landscape. The field of B2B sustainability marketing continues to hold immense untapped potential (Pichler & Hautamäki, 2023).

Combine Finnish know-how on sustainability and digital innovations

5) The integration of digitalisation with sustainable business practices, alongside adherence to digital passport traceability standards, could present significant business opportunities for Finnish nonwoven companies. Given Finland's consistent high performance in the EU's Digital Economy and Society Index, there is a solid foundation for companies to become leaders in the sustainable nonwovens sector, leveraging digital innovation.

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2.2 EU Regulatory Landscape

Noora Raipale

In this chapter, you will learn about the main EU regulations that affect nonwovens, how to comply with these regulations, and how to anticipate future regulatory changes that may impact nonwovens' development activities. This is for you if you are interested to learn about the main resources that can support regulatory compliance with in the development of nonwovens.

Main EU Legislation and Regulations for Nonwovens

Regulations play a significant role in creating more sustainable actions by setting consistent requirements for the industry, as well as encouraging the creation of new innovations. Regulations can present both challenges and opportunities for the industry, as they may require changes in the raw materials, production processes, or end-of-life options of nonwoven products, but they may also stimulate the development of new and more sustainable solutions that can meet market demand and consumer preferences. Therefore, it is important for the nonwovens industry to be aware of existing and upcoming regulations, and to comply with them in order to enhance the sustainability of nonwovens and to gain a competitive advantage.

In the nonwovens industry, regulations and legislation especially target single-use nonwovens. Overall, disposable nonwovens comprise 65–70% of total nonwoven consumption, and, as disposable products, they can generate a huge amount of waste (S&P Global, 2020). In this chapter, we explore the main legislation and regulations that apply to nonwovens to understand what kinds of actions are needed in the industry.

Waste and Waste Framework Directive

In the European Union, the EU Waste Framework Directive (Directive 2008/98/EC) is an important tool for waste management, and this framework applies to all waste streams, including nonwovens. This framework establishes a hierarchy in which waste management options are ranked based on their environmental impact. The highest desirable option in the hierarchy is the prevention of waste, followed by re-use, recycling, recovery, and disposal which is the least preferred or the last option of waste management tools. This directive can be used as a basis for waste management, in which many other directives are based on.

SUP Directive

The Single-Use Plastics (SUP) Directive (Directive (EU) 2019/904) aims to reduce the environmental impact of single-use plastic products, which affects the nonwovens sector especially for disposable hygiene products such as wet wipes, nappies/diapers, and some sanitary products. The directive has introduced bans on certain disposable plastic products together with introducing restrictions on the use of plastics in some single-use products. In addition, SUP requires harmonised marking specifications and other requirements regarding extended producer responsibility (EPR), for example, awareness-raising and the need of separate collection for recycling.

How exactly does SUP affect nonwovens? For example, according to SUP, regenerated cellulosic fibres can be used as raw materials in single-use nonwovens. However, some bio-based polymers such as PHA's and PLA are classified as 'plastic' according to the SUP Directive's definition of plastic, as these are chemically modified polymers. Use of these 'plastics' as raw materials must be marked with a 'plastic in product' marking in sanitary products and wet wipes. In addition to this, especially with regards to chemical binding of nonwovens, many binders still contain latex and are fossil-based. These continue to be excluded from the SUP classification of products containing plastics, but it is good to keep in mind that this might change at some point to target binders as well.

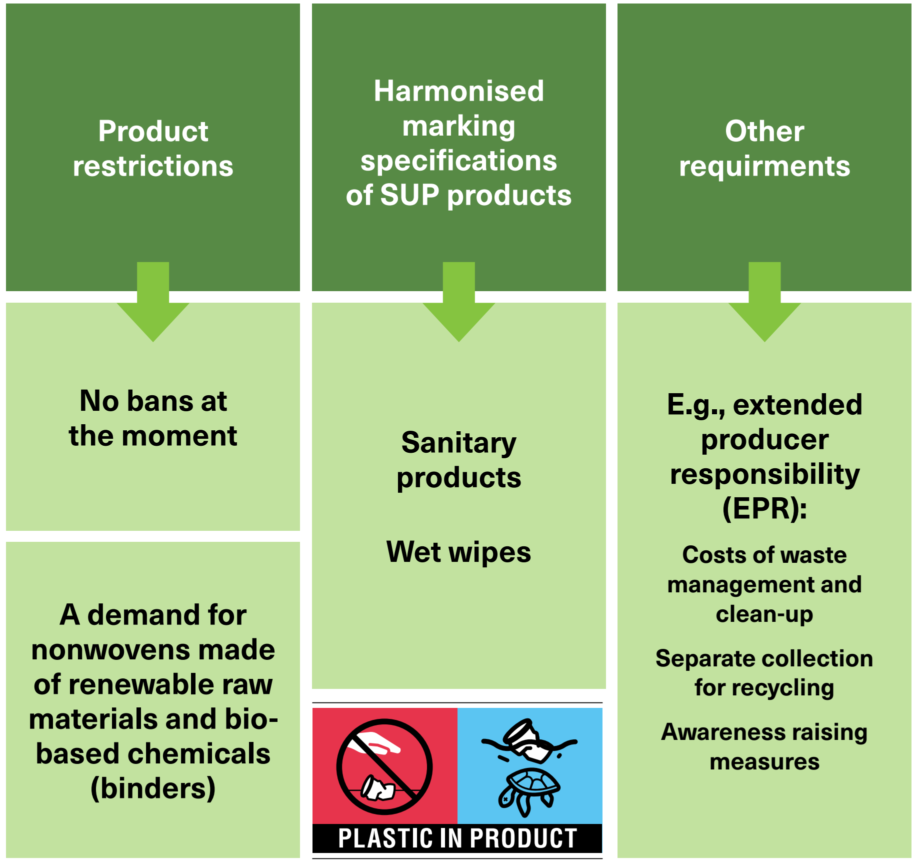

Figure 1. Product restrictions, harmonised marking specifications for SUP products, and other requirements, such as extended producer responsibility (EPR). Plastic in product sign from SUP marking specifications - European Commission (europa.eu).

Regulations on Flushable Wipes

INDA (the Association of the Nonwoven Fabrics Industry) and EDANA (European Disposables and Nonwovens Association) have recognised a gap in legislation on the flushability of disposable wipes, and created tests and methodologies to scientifically identify flushable wipes. They have published Guidance Document for Flushable Nonwovens (EDANA, n.d. a) which has been adapted as the basis for flushability standards and regulations in many countries inside the EU. The guidance especially targets wet wipes, as many wet wipes are not meant to be flushed, and even some wet wipes, which are claimed to be flushable, do not meet the targets of the guidance from INDA and EDANA, so compliance should always be tested whenever flushable wipes are being designed. In addition, in early 2023 INDA and EDANA and their members started a process of ISO standardisation initiative focusing on establishing an international standard for flushability. The decision on establishing the standard has not been taken yet, although the process shows promise (EDANA, n.d. b).

The EU Ecolabel

The EU Ecolabel (Regulation (EC) No 66/2010) is a voluntary certification scheme that helps consumers identify products and services that have a lower environmental impact compared to other similar products. The criteria for obtaining the Ecolabel is revised every three to five years, and the criteria includes, for example, a more sustainable fibre production, a less polluting production process, restrictions on the use of hazardous substances, and a long-lasting product. (European Commission, n.d.)

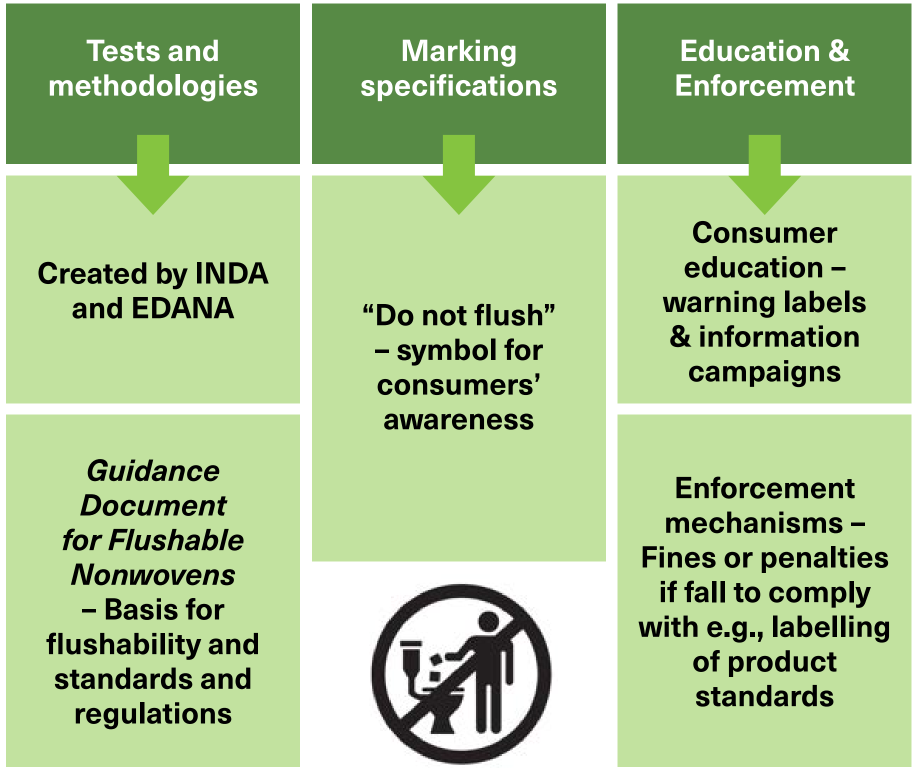

Figure 2. Regulations on flushable wipes include tests and methodologies, marking specifications, and consumer education and enforcement mechanisms. Do not flush symbol from Flushability (edana.org).

CEAP (Circular Economy Action Plan)

The Circular Economy Action Plan (CEAP) (European Commission, 2020) is a policy framework adopted by the European Commission in 2020 that aims to make EU economy more sustainable, circular, and resilient. The framework targets the entire life cycle of products, from designing to processing, consumption and end-of-life of products, aiming to ensure that waste is prevented, and the resources used are kept in the EU economy for as long as possible. The CEAP includes key product value chains, within which packaging, plastics, textiles, and construction and building are related to nonwovens. Further precise actions are listed in the CEAP itself.

REACH Regulation

The REACH Regulation (EC 1907/2006, EDANA, n.d. c.) is a European regulation relating to the registration, evaluation, authorisation and restriction of chemicals. It aims to protect human health and the environment from the risks caused by chemicals. This requires manufacturers and importers of chemicals to register them with the European Chemicals Agency (ECHA) and provide information on their properties, uses and hazards. Regarding nonwovens, this regulation also imposes obligations on downstream users of chemicals, such as nonwoven producers, to ensure safe handling and use of substances. In addition to REACH, an important resource is the Cen Workshop Agreement (CWA) published in the end of 2023, concerning a test method for assessing the potential presence of trace chemicals in absorbent hygiene products (EDANA, n.d. b).

Main EU Initiatives and Policies Affecting the Nonwoven Industry

Green Claims Directive

The Green Claims Directive (European Parliament, 2023) aims to prevent misleading environmental claims, requiring for environmental claims on products to be validated with supporting evidence, which helps consumers in making sustainably conscious purchase decisions. For nonwovens, previous statements such as 'green' and 'more sustainable' could have been used in product labels without proving that the product actually is more sustainable compared to similar products. The Green Claims Directive will change this so that any green claims must be proven with strong evidence.

How can my company comply with the Green Claims Directive?

- Back sustainability claims with scientific evidence.
- Review Environmental Labelling Schemes (ELS) to standardise environmental labelling efforts.
- Choose transparent and verified environmental labels, for example, the EU Ecolabel.

EU Strategy for Sustainable and Circular Textiles

The EU strategy for sustainable and circular textiles (European Commission, 2022) focuses on some of the textile products placed on the EU market, with an aim is to create a more sustainable sector, in which all stages – designing, production, consumption, and waste management of the products – are more sustainable, avoiding overproduction and overconsumption, and focusing on the use of recycled materials. The strategy was published in March 2022, and it is slowly putting mandatory requirements and actions into force including, for example, requirements to make products last longer, easier to repair and recycle, as well as targets on minimum recycled content, tackling greenwashing, and introducing mandatory Extended Producer Responsibility (EPR) rules.

Ecodesign for Sustainable Products Regulations (ESPR)

The proposal for the Ecodesign for Sustainable Products Regulation was published in 2022 (European Commission, 2022), building on the existing Ecodesign Directive, which has only covered energy-related products. The ESPR focuses on a wider range of product groups to significantly improve their circularity and environmental aspects. This means that performance and information requirements are set for almost all physical goods placed on the EU market, thus targeting nonwovens as well.

Main Resources and Tools Helping Nonwoven Value Chains to Comply with Regulations and Access Opportunities

One of the ways to follow future regulatory changes is to monitor the EU policy agenda, and follow the updates from the European Commission, the European Parliament, the Council of the EU, and ECHA. Industry associations, EDANA and INDA, provide a platform for knowledge sharing, innovation, and advocacy for the nonwovens sector. These associations provide information and data to improve the industry, and guidelines to improve the sustainability of the products (e.g., guidance for flushable nonwovens). The nonwovens industry is evolving fast, and new innovations are being introduced continuously. Keeping track of the emerging regulatory landscape helps a great deal in creating new innovations which comply with a sustainable future.

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2.3

Understanding Stakeholders – A Broad Picture

Shruti Dharwadkar**, **Hanna Pihlajarinne** & **Pia Hautamäki

The SUSTAFIT research project assembled a diverse group of sustainable nonwovens value chain stakeholders facing challenges in identifying key industry players across varied application segments. This chapter focuses on pinpointing essential stakeholders in the hygiene and medical segments of nonwovens, aiming to facilitate innovation and sustainability in the nonwovens industry.

Diversity of Stakeholders – A Multitude of Opportunities

When conceptualising the SUSTAFIT research project, a diverse group of stakeholders from the value chain was assembled to create a network focused on studying sustainable nonwovens. However, identifying the key players in the nonwovens industry proved to be a challenging task due to the existence of several distinct application segments within the sector. It became clear, particularly when examining the partner companies' specialised segments, including hygiene and medical, how different these application segments are from each other. Additionally, understanding how to locate the right players was crucial for the project's goal of steering the nonwovens industry toward greater sustainability, with the support of the entire value chain and its varied stakeholders.

Wide range of various players and stakeholders operate in the nonwovens sector. This may impact on sustainability transformation in the field.

This varied nature of the sector is the reason why this chapter concentrates on pinpointing stakeholders who hold critical positions within the nonwovens industry, in the hygiene and medical application segments of nonwovens. The objective of this mapping exercise was to address crucial questions regarding the principal stakeholders who are steering innovation, sustainability, and expansion in the nonwovens sector. Through our experiences in seeking out stakeholders, we recognised that other entities in the nonwovens sector might also benefit from using these tools to identify and engage their stakeholders.

A Practical Tool for Planning: Stakeholder Map

In the realm of stakeholder analysis, there exist various typologies. For this study, we adopted Werther and Chandler's (2011) framework, which identifies three primary stakeholder groups within an organization:

Which of these stakeholder groups do you fit in?

1) **Organizational Stakeholders:** This group is the backbone of the organization, consisting of employees, managers, and stakeholder units. They are the internal drivers of the organization 's mission and daily operations.

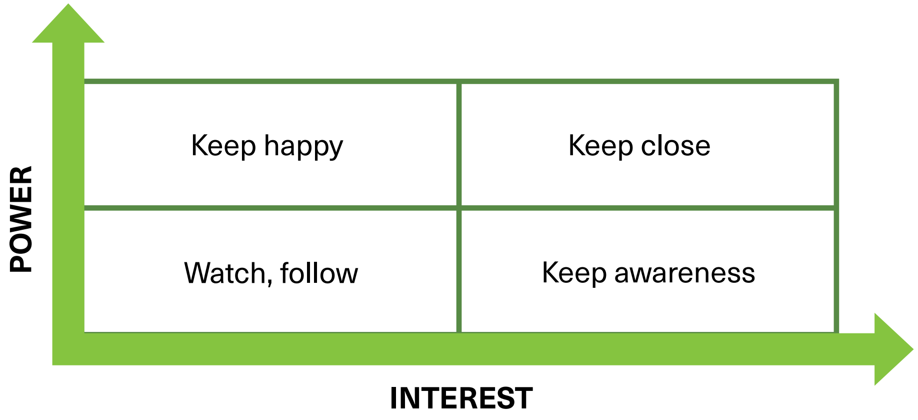
2) **Economic Stakeholders:** Key players in the organization's commercial ecosystem, this group includes customers, competitors, creditors, suppliers, and distributors. They are the external entities that directly engage in economic transactions with the organization.

3) **Societal Stakeholders:** This group extends beyond economic transactions to encompass governments and regulators, local communities, non-profit organizations, NGOs, and the broader ecosystem. They reflect the organization 's social responsibility and its role within the wider community.

Organizational Stakeholders are internal to the organization, while Economic and Societal Stakeholders are external. Economic Stakeholders serve as a bridge connecting the organization with Societal Stakeholders. All three groups operate within a larger tapestry of social, demographic, and technological trends that not only impact the organization but also influence all its stakeholders (Werther & Chandler, 2011).

> *Stakeholder mapping is a simple yet widely used tool for identifying and understanding the stakeholders in a specific area.*

Stakeholder mapping is a critical component of the design thinking philosophy. Recognising all players in the sector and understanding their behaviour, intentions, interrelations, agendas, interests, influence, and resources is essential. This understanding reveals how they can support the organization (Brugha & Varvasovszky, 2000). Armed with this knowledge, you can identify the best partners, manage stakeholders effectively, and understand how future decisions are made. Stakeholder mapping also aids in determining



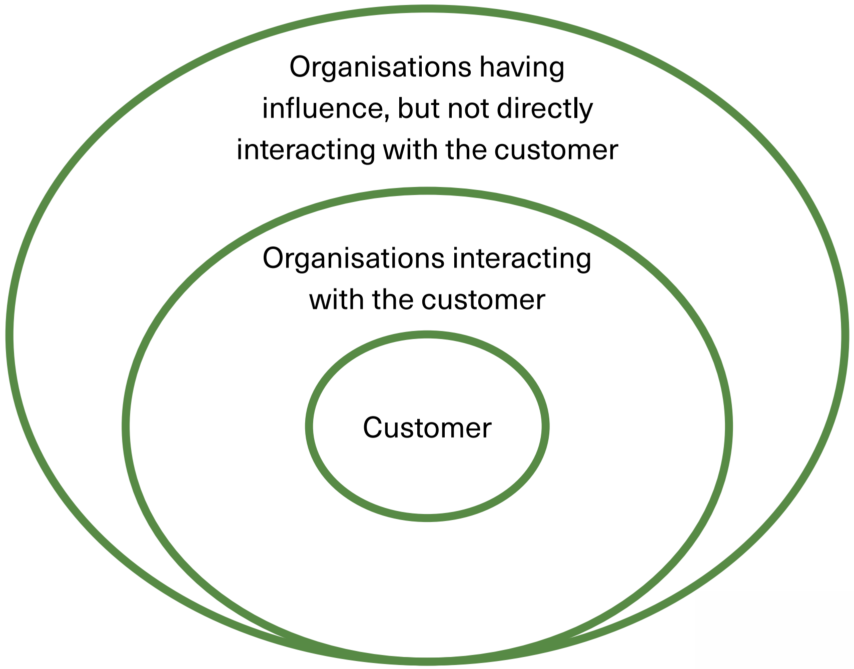


Figure 1. Examples of visual presentations of stakeholder mapping (Source: Own elaboration)

how to collaborate with the different stakeholders. There are various models and templates for visually representing a stakeholder map. Figure 1 offers two simplified examples, demonstrating how stakeholder maps can meet different needs.

The intersection of stakeholder interest in an organization's policy, strategy, or issues, and their capacity to exert influence, creates four distinct categories of stakeholders:

Players:

These stakeholders wield significant power and have a vested interest in the matter at hand. They possess the capability to bolster or undermine the initiative. As the most critical group, they require the highest level of engagement and management by those implementing strategies.

Subjects:

This group has a stake in the issue but lacks substantial influence within the organization.

Crowd:

These are stakeholders with minimal power and interest regarding the current issue. They are more like potential stakeholders rather than active ones.

Context Setters:

Stakeholders in this category have the power to affect change but do not have a direct stake in the specific issue. However, their influence can shape the broader context in which the organization operates. (Ackermann & Eden, 2011).

Nonwovens Industry Renewing Itself

The nonwovens industry is changing when it comes to sustainability. The industry is evolving through the use of new, sustainable raw materials, and there is a need for new innovations that can be sustainable and produced into wide range of different products, in different sectors. There are new players and new stakeholders bringing value to the industry. The initiation of stakeholder mapping within this industry was prompted by the need to understand the key players and acquire a comprehensive understanding of the industry's dynamics. The mapping began with the fundamental question of identifying the influential players shaping the trajectory of the sector.

Did you know that disposable nonwovens account for 65–70% of the overall nonwoven consumption? (S&P Global, 2020)

Single-use nonwoven items like disposable wipes and facemasks pose environmental concerns due to their extensive use of fossil-based plastics, contributing to high carbon footprints, especially when using virgin materials. Improper disposal of these materials leading to landfill and ocean pollution exacerbates the problem by releasing microplastics, harming animals, and the environment. (Raipale, 2023).

This chapter aims to identify stakeholders that occupy pivotal roles in the nonwovens industry. This mapping was developed to answer important questions about the key stakeholders guiding innovation, sustainability, and growth in the nonwovens sector. This review focuses on two nonwovens segments – hygiene and medical.

The medical segment has a wide range of applications including:

- dressings
- surgical masks and gowns
- surgical drapes
- hygiene segment incl. feminine hygiene products
- nappies/diapers
- adult incontinence products

This review was not merely an academic pursuit, but rather a strategic necessity for anyone aiming to navigate the intricate landscape of the nonwovens industry. We concentrated on single-use nonwoven items. For this chapter, we restricted stakeholder mapping to only include companies, and excluded political actors or other influencers.

Mapping the Stakeholders in the Field

To map the company stakeholders in the nonwovens industry, we selected the power/interest grid as our analytical. This model not only aids in identifying stakeholders, but crucially outlines key strategies for managing different categories of stakeholders effectively. The model's development recognises that considering the vast array of stakeholders in organizational management is a challenging and an intricate endeavour. The two most critical variables identified for effective stakeholder management are power and interest. These factors are then used to construct the power/ interest grid, which is illustrated in Figure 1.

Our stakeholder mapping efforts began with a survey of internal stakeholders at SUSTAFIT. The survey revealed that two segments of the nonwoven industry, hygiene and medical, were deemed essential and merited a thorough investigation. This insight provided the foundation for writing this chapter. The chapter's approach is not scholarly in nature but rather serves as a practical illustration of how stakeholders in the nonwovens industry can be identified and mapped.

Application Segments in Stakeholder Mapping

Hygiene – The Most Significant Market Share in Europe in the Nonwovens Industry

The hygiene segment we examined primarily includes nappies/ diapers, feminine hygiene, and adult incontinence products. According to EDANA (2023), this segment stands out as the most substantial, consistently maintaining significant European market shares (including exports) in both weight (28.5% of total delivery in tonnes) and surface area (57.6% in square metres). Notably, within the hygiene segment, baby nappies/diapers command the highest market share, accounting for 62.9% in tonnes and 69.3% in square metres. It is worth mentioning that wipes for personal care, although not considered in this stakeholder study, represent another noteworthy segment.

Medical – Face Masks and Surgical Gowns in Daily Usage

The medical application within the nonwovens industry encompasses a diverse range of end-use products, including surgical gowns and drapes, face masks, wound care items (bandages, dressings, swabs, etc.), and various other medical and surgical products. According to EDANA (2023), spanning almost a decade from 2010 to 2019, the annual sales of European nonwoven medical applications remained consistently around 2,000 million square metres. However, the unforeseen surge in demand for medical products during the COVID-19 pandemic led to a substantial increase, reaching 12,000 million square metres during the period of 2020– 2021. Although the sales have seen a decrease since then, they still surpass pre-pandemic levels.

Stakeholder Mapping: Understanding Key Players in the Nonwovens Industry's Value Network

The stakeholder map resulting from our study is illustrated in Figure 2. We found several **big players** in the nonwovens industry within our selected segments. Kimberly Clark, Suominen, Berry Global, etc. amongst many more globally were recognised as key players, each contributing distinctively to the multifaceted landscape of nonwoven applications. The objective was to comprehend their market presence, innovation strategies, and global influence, acknowledging that a profound understanding of these companies is integral to unravelling the industry's potential and challenges.

Raw Material Suppliers (e.g., Berry Global & Suominen) are positioned at the top of the map, providing essential raw materials, machinery, and equipment necessary for nonwoven production. They play a pivotal role in supplying vital components and resources to nonwoven manufacturers.

At the centre of the map are **the Big Players** or Market leaders (Kimberly Clark, etc.), comprising of companies holding a substantial market share. These entities significantly influence the overall landscape of the nonwovens industry.

Then, there are the **Manufacturers** (e.g., Berry Global & Suominen), companies actively involved in the production of nonwoven materials and the supply of nonwoven products to various industries and B2B customers. Notably, an overlap with the big players suggests that some companies manage most processes in-house.

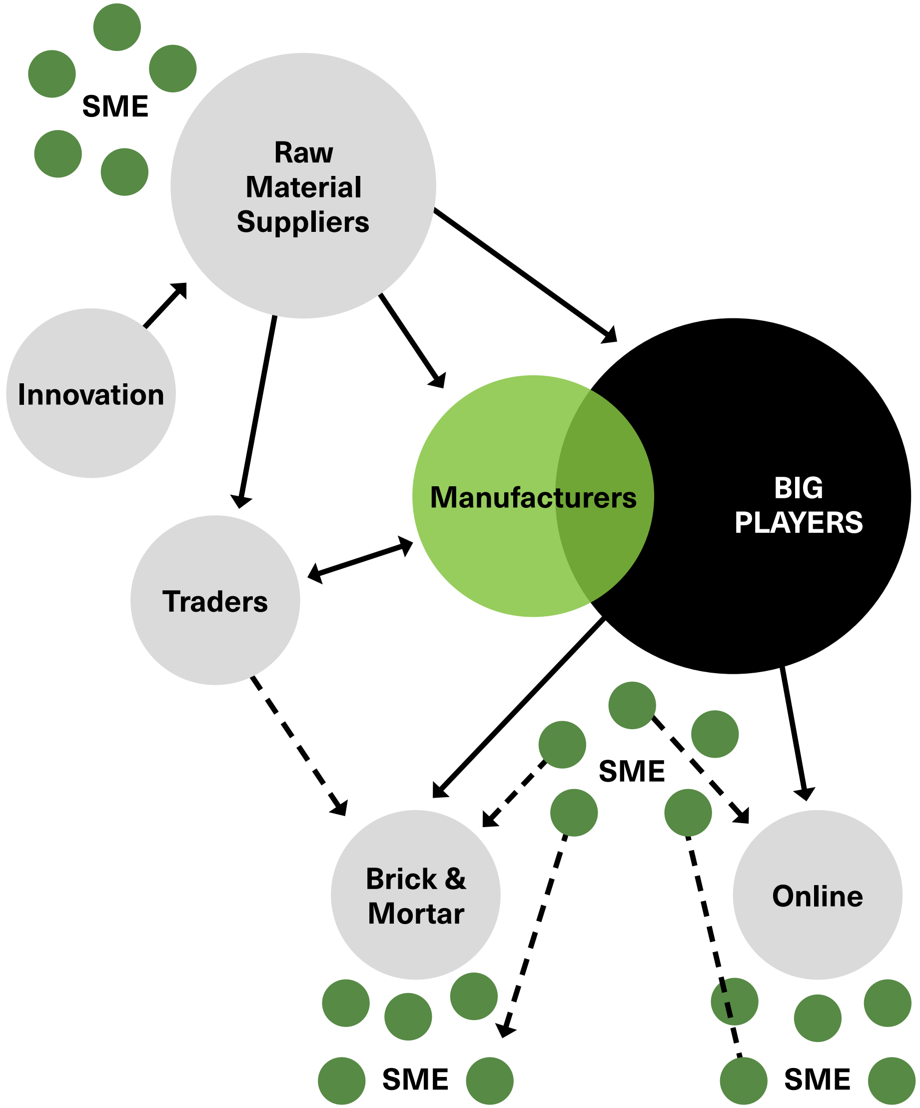


Figure 2. Stakeholder map in the application segments of medical and hygiene (Source: Own elaboration)

Adjacent to raw material suppliers and manufacturers are the **Traders**. These intermediaries serve a critical function in facilitating the distribution of nonwoven products from manufacturers to end-users. Traders contribute to broadening the market reach.

Additionally, a subset of stakeholders falls under the category of **Innovators**. These are companies (Valmet, etc.) not directly affiliated with the nonwovens industry but ones that have introduced applications or machinery designed to enhance specific functions within the nonwovens sector. The distribution channel is bifurcated into two categories: **Brick & Mortar** and **Online**. Brick & Mortar encompasses department stores for hygiene products and pharmacies catering to the medical segment. On the other hand, the Online channel includes major distributors such as Amazon, facilitating a digital avenue for product distribution. Although our mapping exercise's primary focus was on major stakeholders, it is worth noting the presence of numerous Small and Medium Enterprises (SMEs) amongst the raw material suppliers and traders, both in manufacturing as well as in distribution.

The stakeholder mapping initiative in the nonwovens industry, particularly within the hygiene and medical segments, offers crucial insights into market dynamics, innovation strategies, and the global influence of major players such as Kimberly-Clark, Berry Global, and Suominen. The adaptability of the nonwovens industry, demonstrated during the surge in demand for medical products during the COVID-19 pandemic, highlights the industry's resilience. Identifying stakeholders, including raw material suppliers, major companies, manufacturers, traders, and innovators, makes visible the interconnected web that sustains the industry.

Value Network in Action: More Chances for New Players

In this chapter we show how the nonwovens industry and its value chain differentiates from the traditional value chain model. Our stakeholder mapping work shows how the nonwovens industry follows a value chain model, but acts more like a value network (see also Ricciotti, 2019).

> *Based on our review, the value network provides more possibilities for different companies to bring more value for other companies in the value network.*

In a traditional value chain, value creation has been laid out in a traditional 'buyer-supplier' partnership model. However, in a value network model, which seems to be the model the nonwovens industry has adopted, value co-creation and co-development between bigger and smaller players is highlighted.

Based on our findings we suggest that companies looking for new business in sustainable nonwovens can strategically target partnerships with major players. Collaboration with Raw Material Suppliers and Manufacturers is beneficial for the development of new raw material utilisation.

Tap into business opportunities: New companies can develop partnerships with big players, too!

We suggest that the mapping initiative also adds value to the companies in the nonwovens value network in several different ways. For example, stakeholder mapping empowers companies to tailor products and services, explore strategic collaborations, and adapt innovative solutions to navigate the complex nonwovens landscape effectively. Opportunities for partnerships with numerous SMEs among Raw Material Suppliers and Traders highlight potential avenues for growth and sustainability.

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2.4 Business Models in Single-Use Nonwovens

Minna Varheenmaa & ***Pia Hautamäki***

This chapter explores sustainable business models for single-use nonwoven products, highlighting current practices and potential innovations in the industry. It focuses on the impact of EU regulations, environmental standards, and technology on driving change, offering examples of enablers for new business model development.

Are you ready to explore new business ideas within the nonwovens industry?

The SUSTAFIT research initiative, dedicated to developing sustainable, purpose-specific nonwovens, was launched in response to the Finnish industry's imperative to bolster its competitive edge and seize burgeoning opportunities within the expanding market for eco-friendly nonwovens.

EU policies target the mitigation of the environmental crisis, with governmental actions to implement these policies, and stakeholder demands – including those from consumers and investors – acting as pivotal drivers for the nonwovens sector's sustainability enhancement. Environmental activities are currently being pursued across multiple fronts, including academic research, nonwovens industry operations, and EU scrutiny. Nonwovens, characterised by their construction from fibres united through mechanical, chemical, or thermal means, are at the centre of these efforts. Moreover, legislative measures such as the Circular Economy Action Plan, the Plastic Strategy, the Sustainable and Circular Textiles Strategy, and the Ecodesign for Sustainable Products Regulation (ESPR) are pertinent to nonwoven products, which can consist of diverse material compositions. (EC, 2018; 2021; 2022; 2023; EDANA, n.d.).

Despite regulations urging the nonwovens industry toward sustainability, research on the durability, sustainability, and circularity features of nonwovens is less prevalent than studies concentrating on business models (BMs). Moreover, within the academic literature pertaining to business models, a greater emphasis is placed on traditional business models over sustainable ones. Numerous academic publications advocate for more research on sustainable business models to direct industries towards adopting more sustainable practices within their business operations. This is why this chapter focuses on introducing a more academically-built framework of sustainable business models.

Sustainability requirements challenge the traditional definitions:

- SBM Sustainable Business Model: integrates sustainability into a traditional business model
- BM Traditional Business Model: focuses primarily on economic aspects

Exploring Business Models Within the Nonwovens Industry Context

Despite the nonwovens industry's move towards more sustainable business models (SBMs), it is surprising how limited the research is, both in academic literature, and on a practical level. Unlike traditional BMs that primarily focus on economic aspects, SBMs also account for environmental and social considerations, thereby modifying traditional BMs to integrate sustainability. This integration can occur either by embedding sustainability into existing business models or by developing new sustainable business models. In this framework, economic sustainability is supported by social sustainability, which in turn is underpinned by environmental sustainability. Circular business models, which emphasise reuse and recycling, are a subset of SBMs. (Bocken, 2016; Lozano, 2018; Aalto University n.d.; Hunt, 2023)

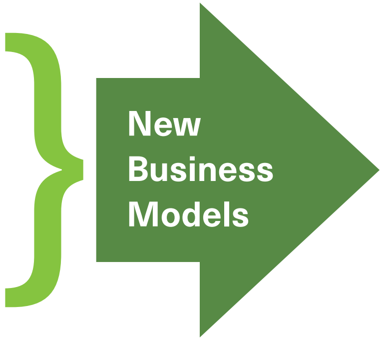
Business Models in a Single-Use Nonwovens Industry: Focus on Diapers and Wipes

As outlined in the Master's Thesis by Rouhento (2023), we focus on the SBMs currently in use in the nonwovens industry. The study, carried out as a part of the SUSTAFIT research project, specifically examined single-use nonwoven products such as nappies/ diapers and wipes within their respective value chains. Through a methodology that included reviewing company websites, distributing questionnaires, and conducting semi-structured interviews, the key findings revealed that, beyond economic value, the SBMs in this product domain also deliver significant environmental and societal benefits. The sustainable practices identified relate to choices in raw materials, material efficiency, raw material features, circular economy principles, and social considerations such as product safety and sustainable production methods. According to Rouhento's (2023), for a business model to be deemed sustainable, companies must apply these considerations throughout their product's life cycle.

An analysis of company websites and semi-structured interviews revealed sustainable features and practices associated with nonwoven products. These were categorised into five areas: raw materials used in the products, characteristics of these raw materials, societal concerns, circular economy initiatives, and sustainable production techniques. By integrating suitable combinations of these features and practices, some approaches can be recognised as sustainable business models (SBMs) that generate value from economic, social, and environmental perspectives – often referred to as the Triple Bottom Line (TBL). Among the 64 companies analysed, 70% incorporated sustainability into their business model in some form (Rouhento, 2023). This finding aligns with similar outcomes from previous research (Hunt, 2023), further validating these academic insights.

IMPORTANT ASPECTS TO TAKE INTO ACCOUNT FOR SUSTAINABLE NONWOVEN PRODUCTS

- **Raw materials used**
- **Characteristics of raw materials**
- **Societal concerns**
- **Circular economy initiatives**
- **Sustainable production techniques**



What would be your way to shift towards sustainable business models?

Furthermore, within the value chains of the diaper and wipe segments, the observed sustainable business practices or models were largely similar, with the exceptions being the flushability feature exclusive to wipes, and the product life extension specific to diapers. The most commonly employed strategies include choices in raw materials, material efficiency, adherence to circular economy principles, and social considerations such as product safety. (Rouhento, 2023)

For diapers, the most critical sustainability aspect is the health and safety of the product. This requirement sets high standards for the quality of raw materials, which are typically natural fibres or bio-based materials when labelled as sustainable, with recycled content being marginal. Chemically recycled polymers and bio-based polymers, for example, are already used in rolled goods for diapers (Rouhento, 2023).

End-of-life scenarios are crucial for the sustainability of diapers. Due to their complex material composition and non-biodegradable components, such as Superabsorbent Polymers (SAP), they are generally disposed of as mixed waste and then landfilled or incinerated as energy waste. Despite the lack of waste handling infrastructure, many companies already offer biodegradable, compostable, or recyclable diapers, enhancing sustainability (Rouhento, 2023).

An example of a circular business model is a company that offers diaper products as a service, creating value from waste, and returning resources to the cycle. This company accepts back used diapers and wipes, processing the waste through composting or pyrolysis into soil or char (Rouhento, 2023; Dyper, n.d.).

Can you think of another way to generate value within the nonwovens sector? Diapers as-a-service?

What can be done with hybrid diapers which have a reusable layer and a single-use layer?

Additionally, a product life extension model can be implemented, resulting in reusable products. For instance, in hybrid diapers, the outer layer is reusable while the inner layer is a single-use, replaceable material (nonwoven type). More sustainable alternative materials must compete with the superior properties, price, and user acceptance of some traditional materials (Rouhento, 2023).

In summary, within the value chain for wipes, choosing sustainable raw materials emerged as the most prevalent sustainable business model. The simpler composition of wipes, coupled with their broader range of applications, allows for a wider selection of materials for the nonwoven component, compared to diapers. The majority of companies highlighted biodegradability and flushability as key sustainable attributes of their raw materials. Additionally, the chemical composition of the wipe is designed to be safe for human use and used only when necessary, with health and safety standards varying depending on the product's intended use. Companies recognise the Single-Use Plastics (SUP) Directive as a pivotal force in steering them towards sustainability, and encouraging the elimination of plastics in their wipes (Rouhento, 2023).

Driving Sustainable Business Model Adoption in the Nonwovens Industry: The Roles of Standardisation, Environmental Labelling, and Digitalisation

Recently, several standards have been developed, or are under development, by international standardisation working groups. These standards focus on business models, sustainability, and the circular economy across various industries. Among these, three significant standards related to the circular economy are set to be published soon, as detailed in Table 1. The ISO 14000 series addresses the integration of environmental management systems within organizational management systems. ISO 14001, the most renowned standard in the series, was published 20 years ago. Additionally, ISO 14006 provides guidelines for incorporating ecodesign, and ISO 14009 offers guidance for enhancing material circulation design and development within companies in a systematic way. (International Organization for Standardization, n.d., n.d.)

If you are interested in Sustainable Business Models in an industry that is hugely changing and offering new possibilities, **these ISO standards will guide you on your journey:**

Table 1. Standards for circular economy and environmental management systems

Circular Economy Standards		
ISO 59004:2024	Circular economy	Vocabulary, principles and guidance for implementation
ISO 59010:2024	Circular economy	Guidance on the transition of business models and value networks
ISO 59020:2024	Circular economy	Measuring and assessing circularity performance

Environmental Management System Standards (ISO 14000 Series)		
ISO 14001:2015	Environmental management systems	Requirements with guidance for use
ISO 14006:2020	Environmental management systems	Guidelines for incorporating ecodesign
ISO 14009:2020	Environmental management systems	Guidelines for incorporating material circulation in design and development

Environmental labels and certificates aim to enhance sustainability and environmental thinking when manufacturing, providing, consuming, and disposing products in the end of life. They have for example, restrictions or maximum content criteria for using harmful or hazardous chemicals in production and in products, or guidelines on how to save natural resources or extend the life of the products. These labels and systems provide confidence that sustainability requirements have been fulfilled according to set criteria, which will help consumers to make sustainable choices.

- Forest Stewardship Council (FSC) certifies forests that are used in responsible manner.
- International Sustainability & Carbon Certification ISCC Plus uses a mass balance system, ensuring the amount of recycled or bio-based content in the feedstocks of production and its traceability.
- Nordic Swan Label has sustainability criteria for sanitary products such as nappies/diapers and wipes, and for their producers. For example, most of the recycled raw materials are not allowed to be used in sanitary nonwoven products.

(FSC, n.d; Nordic Ecolabel, n.d.; ISCC System, n.d.)

In addition to Standardisation and Environmental Labelling, new business models for single-use nonwovens necessitate ecosystems where digitalisation and servitisation could significantly contribute as enablers for the development of innovative business models. A change in the business model of one company can also impact other companies within the ecosystem, leading to dynamic business models that are constantly being restructured. Knowledge sharing, networking, and close cooperation with industrial associations, research organizations, universities, and political institutions can assist manufacturing companies in rapidly acquiring information and exchanging knowledge across industries. Consequently, companies could more swiftly learn how to implement and leverage the technological advancements of Industry 4.0, not just to enhance efficiency but also to support SMEs in their innovation-driven business models. The transfer of digitalisation and digital technologies facilitates data exchange and fosters the integration of actors along the value chain. Such a shift towards innovation ecosystems from traditional supply chains would require support and information from policy decision-makers. (Müller, 2020; Kohtamäki, 2019; Favoretto, 2022).

The future sustainability of nonwovens is expected to focus on the selection of sustainable raw materials, necessitating further evaluations of their sustainability. Life Cycle Assessment (LCA) analyses could play a critical role in this evaluation. Studies, such as one comparing garment rental to traditional selling models incorporating LCA analyses, have demonstrated promising environmental benefits (Goffetti, 2020). Additionally, the aspect of value creation should be examined, considering the societal and environmental benefits alongside traditional economic values. Circular economy business models offer innovative approaches for utilising recycled content in products and recovering valuable raw materials. Consumers are identified as key drivers of systemic change, raising the question of how to enhance their awareness and decision-making towards sustainable options. This also applies to public sector procurement practices, emphasising the need for guidance towards more sustainable choices (Rouhento, 2023).

Furthermore, the inclusion of the Digital Product Passport in the EU's Textile Strategy aims to facilitate the tracing of raw materials used in production and substantiate sustainability claims associated with the products. This approach was explored in the sustainable and smart textiles project, culminating in a demo garment trial involving production chain companies (Kerkola, 2023).

Think about how standardisation, environmental labelling, and digitalisation could help you on your way to grow new business in the nonwovens industry?

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2.5 Segment-Specific Sustainability Strategies

Noora Raipale** & **Pirjo Heikkilä

In this chapter, you will learn why and what kind of tailored sustainable actions are needed for different nonwoven products with varying needs, lifetimes, and technical requirements. From single-use hygiene products to durable industrial applications, the spectrum of nonwovens is wide and needs exploration of tailored sustainability strategies. This is for you if you want to learn more about the key sustainability strategies to focus on in different nonwoven segments.

Importance and Relevance of Targeted Sustainability Strategies for the Industry and Society

The nonwovens sector stands as a unique sector, interwoven into our daily lives in diverse forms. From disposable hygiene products to high-performance industrial applications, nonwovens require a targeted strategy depending on the needs of a specific product. Their varying, dynamic nature brings in a critical challenge – how to create products with varying needs, functionalities, and lifetimes whilst considering shared environmental responsibilities? Consider a single-use wet wipe and a durable geotextile fabric. One is designed for a purpose only lasting seconds or minutes, while the other is meant for months, even a year, of extended service. In addition, the needs for these applications vary significantly, as the purpose and intended use of these products is totally different. These are just a few examples underscoring the need for targeted sustainability strategies.

According to standard ISO 14006 (2020), life cycle thinking is important in sustainable business to focus more on circular rather than linear economy (International Organization for Standardization, n.d.). Life cycle thinking aims to take relevant environmental aspects into consideration in every step of the life cycle of the product, as shown in Figure 1.

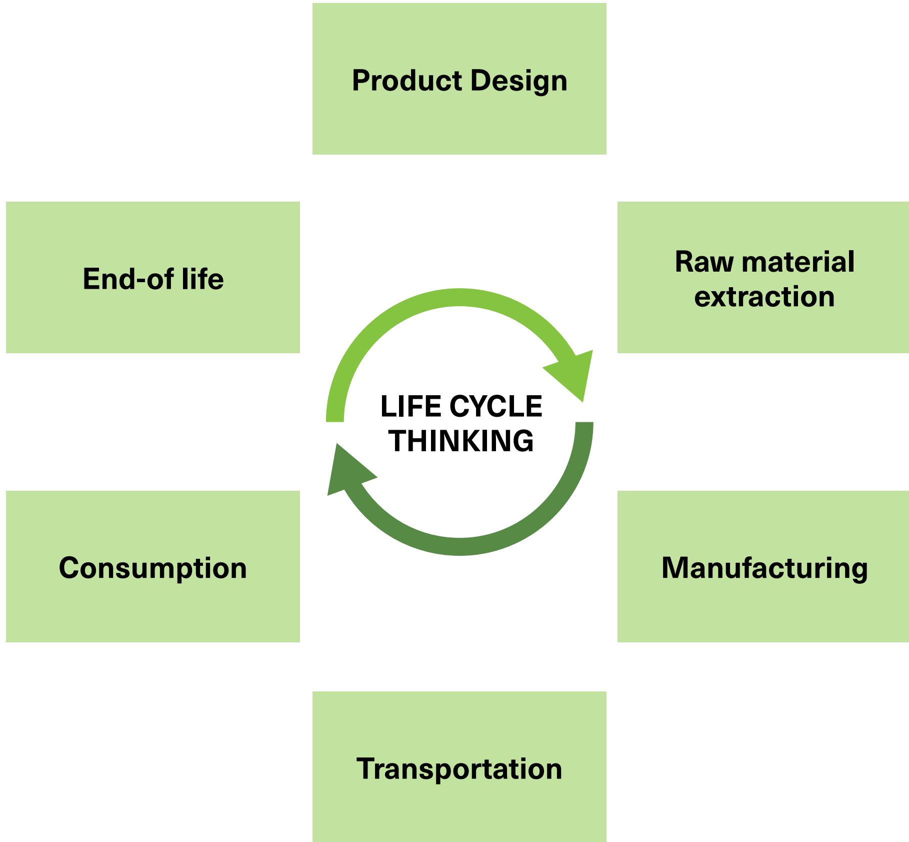

Figure 1. In life cycle thinking environmental aspects need to be considered in every step of the product life cycle.

Nonwoven Segments and Their Requirements

The most common nonwoven segments can be categorised in three different classes based on the lifetime of the product:

1. **Single-use and short-term products have a use time ranging from minutes to hours**

   For example, wet wipes, medical products such as face masks, and nappies/diapers and other hygiene products

2. **Multi-use and/or medium-term have a use time ranging from days to months**

   For example, HVAC and liquid filters, some household abrasives, and crop covers and similar agriculture products

3. **Long-life and permanent have a use time over a year**

   For example, geotextiles used for erosion control, thermal insulation materials used in construction, and acoustic materials in automotives

Nonwoven segments can be categorised by the complexity of the processing and the technical requirements level needed. These can refer, for example, to specific functionalities or performance.

In Figure 2, different nonwoven product segments are positioned in relation to their lifetime and technical requirements in order to illustrate the spectrum of nonwoven products, ranging from those with low complexity and short lifetimes, to those with high complexity and long lifetimes. Within some of the segments, there is an overlap between different technical requirement levels and lifetimes, as the lifetime of the product together with technical requirements vary depending on the situation. Figure 2 can be used as a guidance for professionals in the nonwovens industry to identify the position of the specific product within this framework, and to understand what kinds of sustainability strategies are needed for a product in certain position.

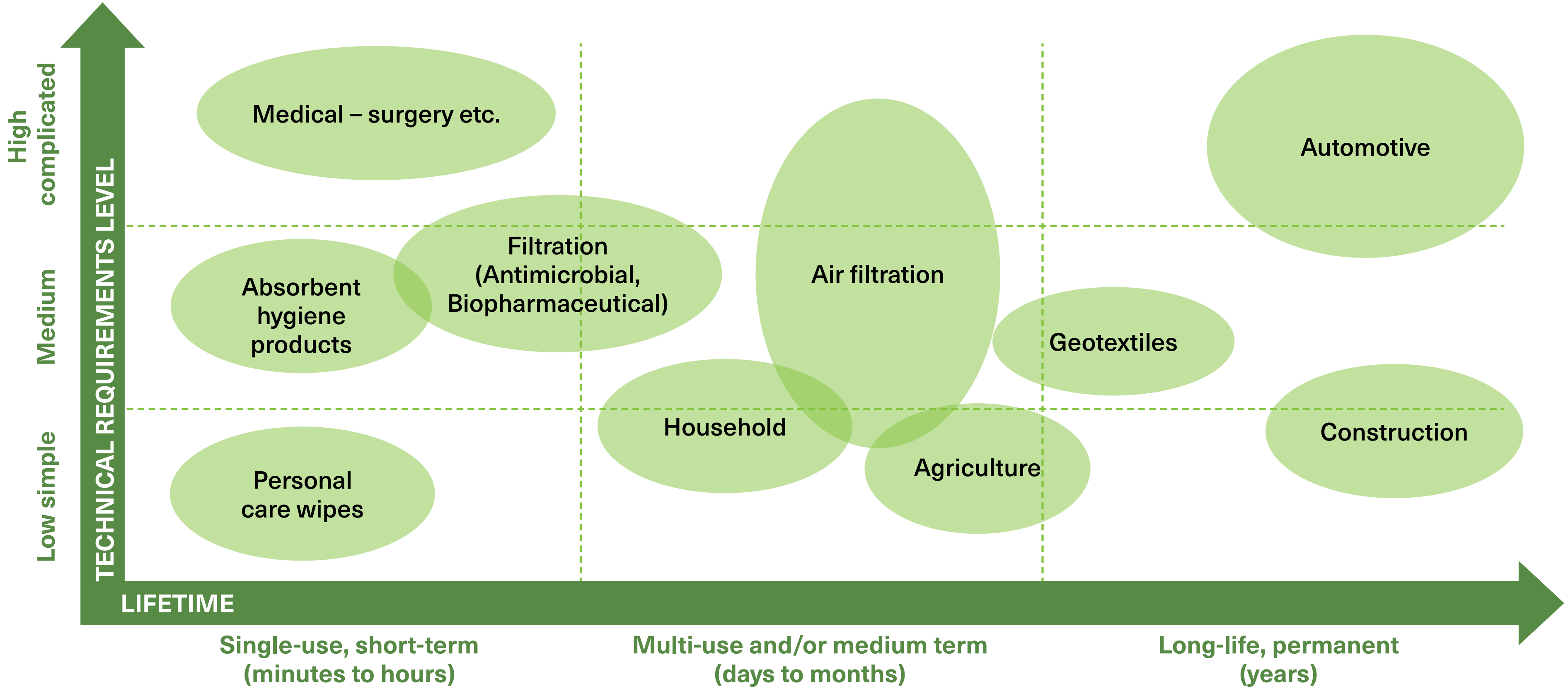

Figure 2. Positioning of different nonwoven product segments in relation to their lifetime and technical requirements.

As we navigate the diverse applications of nonwovens, it becomes clear that there is not a one-size-fits-all approach regarding sustainability strategies. Tailoring strategies to the unique requirements of each segment ensures a harmonious blend of functionality, requirements, and environmental responsibility.

Nonwovens' Sustainability Dimensions

To create more sustainable practices in different nonwoven segments, it is important to understand where changes are possible. Here, three different dimensions have been created to cover the various aspects of how to enhance sustainability (see Figure 3):

1) **Product Concept** includes product and service design, considering the whole life cycle of the product.
2) **Materials** includes material sourcing, and source of the materials, mainly focusing on bio-based, biodegradable, recycled, or recyclable materials.
3) **Processes & Technologies** includes greener options in manufacturing, for example, lower water and energy consumption, greener energy, and in-house recycling.

This kind of a multi-dimensional approach is key to achieve sustainability. By considering each of these dimensions in the design and manufacturing process, a product can be created that is not only functional and attractive but also environmentally responsible.

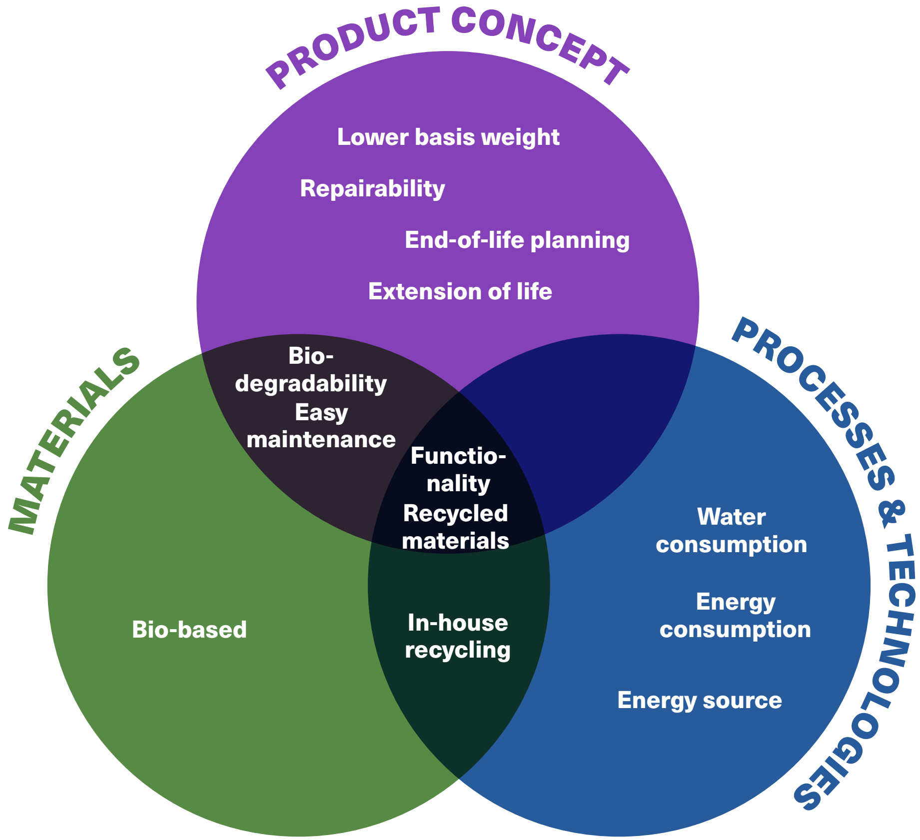

Figure 3. Dimensions of nonwovens' sustainability including sustainable actions to focus on in different nonwoven segments.

Applying Sustainability Strategies to Different Segments

Through a set of case studies, we dive deeper into tailored sustainability strategies, from disposable hygiene essentials to robust industrial applications. From these case studies, players in the field of nonwovens have an opportunity to learn, and by embracing these strategies, the nonwovens sector can shape a more sustainable future. Here, we have listed general advice on what should be considered in nonwovens with varying lifetimes. More specific case examples, including product groups, can be found in the SUSTAFIT project report 'Sustainability strategies for nonwovens'.

Disposable, Single-Use

When considering sustainability strategies in disposable, single-use nonwovens, such as wet wipes and nappies/diapers, we challenge the nonwovens industry to find new ways of thinking and doing:

- **Let's shake up the whole Product Concept:**
  As single-use products can result in massive amounts of waste, focusing on end-of-life and waste management is crucial. **Minimising the amount of material** without compromising performance, together with planning proper disposal methods and encouraging recycling can reduce environmental impacts. An example of designing a product for its end-of-life is deciding how strong the product should be: high wet strength can become an issue in flushable nonwovens, but if the nonwoven product is mechanically or chemically recycled, the strength of the product is not an issue.
- **Let's be creative in Materials Selection:**
  The choice of raw materials can significantly impact a product's environmental footprint. Ideally, products should be made from renewable or recycled materials which are also biodegradable and/or recyclable to minimise their environmental impacts. In this case, Life Cycle Assessment (LCA) is an important tool to check that the replacement of a previously used material with a new one is truly a more sustainable choice.
- **It's time to rethink Processes and Technologies:**
  Manufacturing processes should be optimised to minimise energy and water use. This could involve using energy-efficient machinery, optimising production lines for minimal energy waste, or recovering and reusing heat and water generated during production. Ways of improving sustainability in the process are, for example, recycling of wastewater and in-house recycling of raw materials. Exploration of novel technologies is another solution to produce more sustainable products.

Multi-Use & Medium-Term

For multi-use and medium-term nonwovens, such as the nonwovens used in agriculture, household and air filtration, we challenge you to:

- **Let's shake up the whole Product Concept:** Multi-use nonwovens should be designed for durability and longevity to withstand multiple uses or longer time without losing functionality. In addition to this, it is important to consider maintenance, as easy-to-clean features can extend products lifetimes, reducing the need for replacement as well as reducing waste. Consumer education is also important: clear and simple user instructions on the maintenance of a product extend the product's lifetime.
- **Let's be creative in Materials Selection:** For multi-use nonwovens, it is important to make sure that the resources used result in the desired, or prolonged, lifetime, without faults in the product due to structural properties, such as low mechanical strength, decreasing the need of a replacement. However, the raw material type together with end-of-life options is also important, so the focus should be to improve sustainability by introducing new bio-based or recycled options with sustainable end-of-life options, such as recycling or biodegradation, as long as the functionality and required product characteristics can be kept high together with focusing on long, or the desired, lifetime.
- **It's time to rethink Processes and Technologies:** The consumption of water and energy in production processes is important in the production of multi-use and/or medium-term nonwoven products as well, and it is important to explore more energy-efficient and water-saving processes, in the same way as with disposable nonwovens. In medium-term nonwovens, certain product functionalities can be important, and testing can reveal if the required functionalities are possible to be created with less or greener chemicals.

Long-Life, Durable

Long-life and durable nonwovens, such as nonwovens used in automotive, construction, or geotextiles, need to last for a long time, from over a year to many years. We challenge you to consider these important sustainable practices when creating long-life nonwovens:

- **Let's shake up the whole Product Concept:**
  Long-life products should be designed for a long lifespan, reducing the need for replacement, and thereby minimising waste. This means that a product should be durable, so that the nonwoven material can stand their use conditions without losing their performance or mechanical properties. End-of-life planning of the materials is important especially with highly functional products, as the materials can be of high quality, and thus suitable for recycling into secondary raw material.
- **Let's be creative in Materials Selection:**
  In many long-life and durable nonwoven applications, an important factor to focus on in the materials selection is to find and use materials that can lower the weight of the product together with lowering the amount of the materials to be used, while still offering the desired functionalities and product performance. In addition, regulations for recycled content can affect, for example, the automotive sector, in which a variety of long-life and durable nonwovens are used.
- **It's time to rethink Processes and Technologies:**
  When processing long-life and durable nonwovens, in-house-recycling is important. This means, for example, reducing fibre waste and introducing better circulation of wastewater. In addition, greener energy sources can be used in the production to make more sustainable shifts in the production process, as energy and water consumption cannot always be decreased in order to keep the high performance level of the products.

Future Directions, Research Needs and Business Opportunities for Improving Sustainability

In this chapter, we have explored why targeted sustainability strategies for nonwovens are becoming not just a choice but a necessity. As we look towards the future of the nonwovens industry, sustainability emerges as a key area to focus on. The path to a more sustainable future requires a considerable choice of sustainability strategies to follow, which means that we need to know the needs, lifetime, and technical requirements of the intended product. Here are some future directions research and business ventures to keep in mind:

Material innovations:

Research and development of new materials, particularly those that are renewable, recycled, biodegradable, or recycled, is of high importance.

> *FOR BUSINESSES: New innovations can turn into new business opportunities! New innovations can also change your position in value chain.*

Efficient and sustainable manufacturing processes:

There is a need for research into more efficient and sustainable manufacturing processes that reduce energy consumption and minimise waste.

> *FOR BUSINESSES: New manufacturing processes can enable more sustainable products by decreasing, for example, energy or water consumption.*

Product life cycle analysis:

Comprehensive studies on the LCA of nonwoven products can provide valuable insights into where improvements can be made to enhance sustainability.

> *FOR BUSINESSES: You might find insights on how to improve your products with a proper LCA analysis!*

Regulations and standards:

As the industry moves towards more sustainable practices, there will be a need for clear regulations and standards that guide the transition, and it is important to follow the development of these regulations and standards.

> *FOR BUSINESSES: Think about whether you want to be an early adopter driving new business and doing things first, or whether you want to follow regulations as they are set?*

Consumer education and opinion leader position:

There is a need for research and the right kinds of actions into effective methods of consumer education. Consumers play a crucial role in driving demand for sustainable products, and educating them about the benefits of such products can significantly boost their adoption.

> *FOR BUSINESSES: The company or organization that rises above others as an opinion or thought leader might collect the biggest wins!*

In conclusion, the path towards more sustainable products in the nonwovens industry is a multi-dimensional one, requiring efforts in different dimensions of material innovations, process efficiency, and design which considers LCA, together with regulatory development, and consumer education. We hope that this chapter inspires further research and innovation in these areas, paving the way for a more sustainable future for the nonwovens industry.

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3.

TECHNICAL PERSPECTIVES

The third section of this workbook, Technical Perspectives, explores the key factors around the manufacturing of more sustainable nonwovens. This section is divided into six chapters, each focusing on a different aspect of technical perspectives on sustainable nonwovens. In this section we highlight what kinds of sustainable raw materials, fibres and polymers there are, and discusses their benefits, availability and in what kind of nonwoven applications these raw materials can be used. We further explore man-made cellulosic fibres in more detail, including their history and emerging technologies with which more sustainable man-made cellulosic fibres can be created. We also discuss different bonding strategies for nonwovens, especially focusing on how to make more sustainable choices in bonding solutions for nonwovens. Additionally, we explore ways to increase the potential of cellulosic nonwovens via functionalisation, focusing on hydrophobisation and antimicrobial properties, and we discuss varying end-of-life options for nonwovens, and how, in the SUSTAFIT project, disintegration tests were carried out for produced nonwovens. Lastly, we introduce piloting as a path to more sustainable nonwovens, explaining the kinds of piloting possibilities that can be made use of at the VTT Technical Research Centre of Finland and at the Tampere University of Applied Sciences.

3.1 Selecting Sustainable Raw Materials

Olamide Badara** & **Marja Rissanen

This chapter highlights key factors to be considered when introducing sustainable fibres and polymers to nonwovens. It also provides a list of examples of important sustainable fibres and polymers, and discusses their performance benefits, availability, and common nonwoven applications. This is for you if you want to learn more about sustainable raw materials.

As concerns about the environmental impact of fossil-based raw materials in connection with plastic waste continue to grow, researchers are increasingly focusing on developing new alternatives to replace them.

Did you know that fossil-based fibres and polymers dominate the nonwovens industry due to their low cost and easy processability? (Yan, 2016; EDANA, 2023)

Sustainable polymers and fibres are gradually gaining ground and reshaping the nonwovens sector. This gradual shift from non-biodegradable plastics to biodegradable materials and the use of recycled materials aims to promote the development of environmentally friendly and sustainable nonwovens.

When introducing alternative fibres and polymers to nonwovens, some important factors need to be considered. These include factors such as process compatibility (i.e., raw material compatibility with existing manufacturing equipment) as well as raw material availability, and cost-effectiveness.

By implementing best practices around production process compatibility, raw material availability, cost-effectiveness, lifespan, and end-of-life of a product, you might have a recipe for a new business!

Additionally, it is essential to consider the properties offered by new raw materials and their potential impact on the performance, lifespan, and end-of-life of the nonwoven product (Tronci & Russell, 2022). Aspects such as biodegradability and recyclability should also be considered in order to minimise the product's environmental impact at the end of its life (Tronci & Russell, 2022).

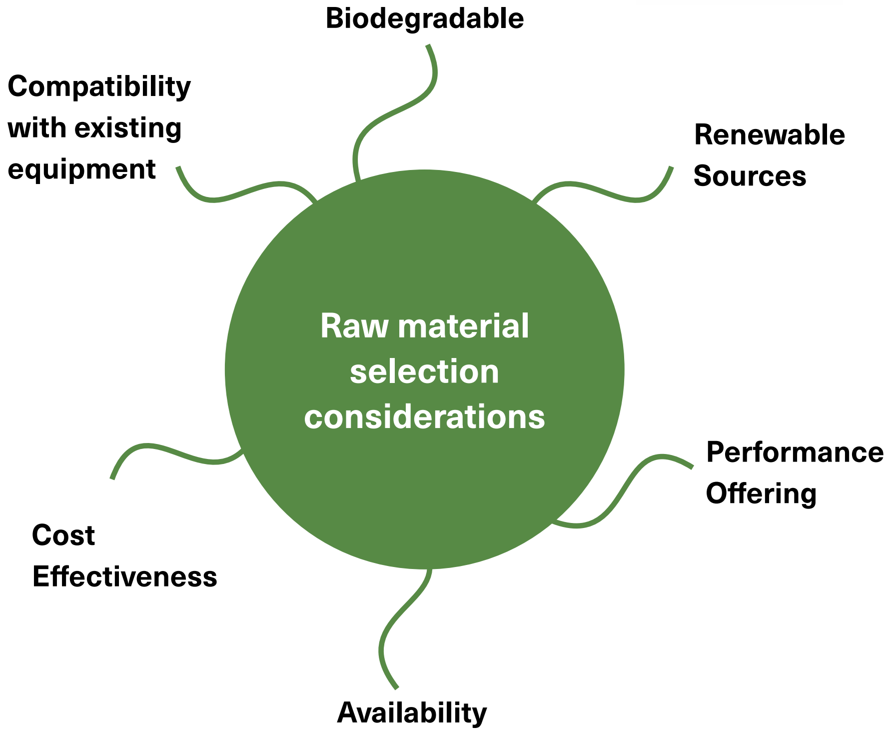

Figure 1: Some important raw materials selection considerations

This chapter provides a list of key sustainable fibres and polymers that can serve as alternatives to existing traditional raw materials based on availability. It also briefly discusses their benefits, availability, and common applications. These materials can be divided into five broad groups: natural cellulose-based fibres, man-made cellulosic fibres, biopolymers, partially bio-based fibres, and recycled fibres.

Natural cellulose-based fibres are gaining popularity in the nonwovens industry due to their renewable sources and benefits such as biodegradability, as well as their reduced environmental impact. Examples include cotton and bast fibres such as jute, flax, and hemp.

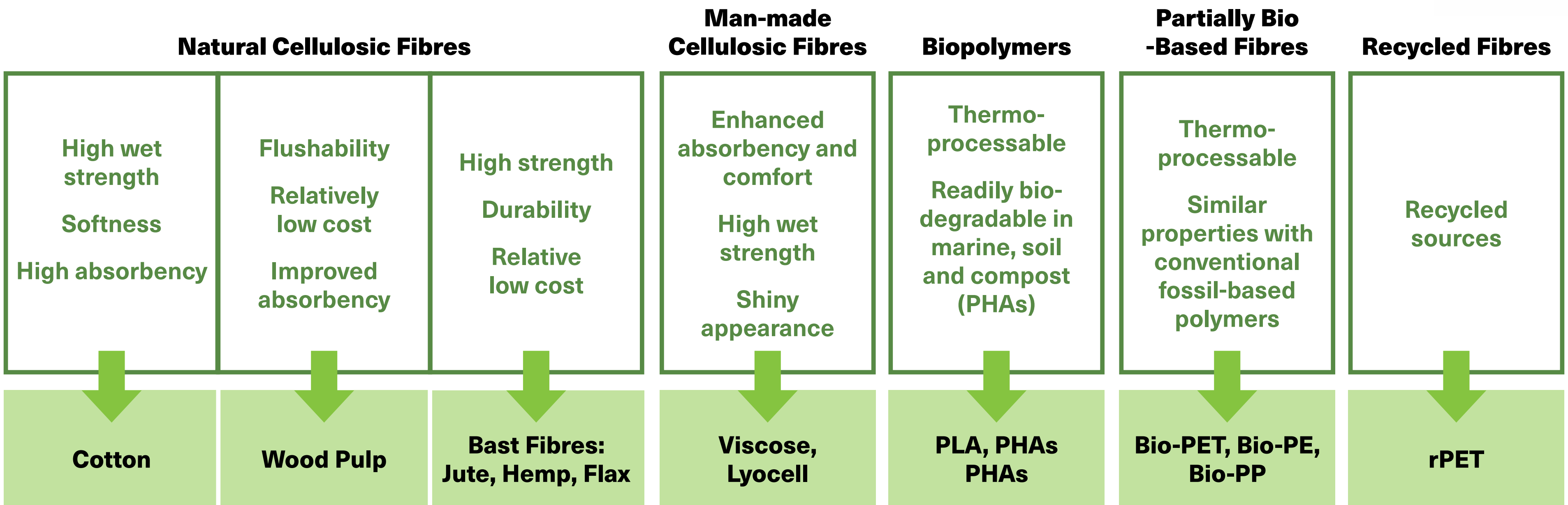

Figure 2: Examples of some key sustainable fibres and polymers used in nonwovens, and their performance offerings.

Possible sustainable raw materials

Cotton is a traditional, absorbent natural fibre

Cotton is the natural fibre with the highest volume. Global production of cotton was 25.5 million tonnes in 2022 (Textile Exchange, 2023). Cotton is noted for its softness, high strength when wet, breathability, and high absorbency, while jute, flax, and hemp offer high strength, durability, and a relatively low cost (Tronci & Russell, 2022; Mather & Wardman, 2015). Cotton is commonly used in hygiene applications such as female hygiene products, wipes, and nappies/diapers, filters, bandages, and wound dressings (Tronci & Russell, 2022; Santos et al., 2021).

Bast fibres such as jute and hemp are a growing opportunity

Bast fibres are cellulosic fibres obtained from the stem of plants. Global fibre production in 2022 of bast fibres included 3.4 million tonnes of jute: 380,000 tonnes of flax, and 300,000 tonnes of hemp (Textile Exchange, 2023). The potential of bast fibres in nonwoven applications is increasingly recognised due to their minimal water and pesticide consumption during cultivation (compared to cotton), making them a highly sustainable choice (La Rosa & Grammatikos, 2019). However, due to their coarse and stiff nature, they have not been commonly used in hygiene applications; their use has been limited to applications where fineness and flexibility are unimportant (Mather & Wardman, 2015). Jute, flax, and hemp fibres are widely used in automotive interiors, sound insulation applications (such as ceiling panels, wall coverings, and room dividers), horticulture, and furniture applications (such as furniture and mattress fillings) (Tronci & Russell, 2022).

New processing and treatment advancements have been made to improve the quality of raw bast fibres, particularly hemp fibres, to transform coarse fibres into softer, more uniform and more easily processable fibres with better performance. for use in broader nonwoven applications including hygiene products such as industrial wipes and personal care wipes (Finnis, 2024; Bast Fibre Tech, 2024). Bast fibres can be combined with other cellulosic fibres to enhance their strength and reduce costs. One recent development is the combination of hemp fibres with other cellulose-based fibres in nonwoven applications, such as in BIOLACE natura wipes (a completely plastic-free product by Suominen) (Suominen, 2022).

Wood pulp and straw pulp are other biodegradable and renewable sources

Wood pulp and straw pulp are another interesting group of natural cellulosic fibres. They are noted for their biodegradability and renewable source. Wood pulp and straw pulp are obtained from mechanical and chemical treatment of wood or non-wood agricultural waste, such as rice, barley, and wheat (Santos et al., 2021). The use of straw pulp is limited due to its lower strength properties compared to wood pulp, and its restricted availability (Hart, 2020). Wood pulp has been commonly used in hygiene hydroentangled nonwoven applications such as baby and personal care wipes, as well as in industrial wipes, absorbent cores of nappies/diapers and female napkins, and filters (Tronci & Russell, 2022). Due to its low wet strength, wood pulp is usually combined with cotton, bast fibres, and MMCFs (Tronci & Russell, 2022; Nandgaonkar, 2024). This helps nonwoven products containing wood pulp remain intact even when wet. Wood pulp is of relatively lower cost when compared with cotton and man-made cellulosic fibres (Tronci & Russell, 2022; Santos et al., 2021). Wood pulp is known to offer improved absorbency and flushability or dispersibility possibilities (at 60–75 wt% inclusion when combined with other cellulosic fibres) (Weston, 2024). Hence, it aids cost savings and property optimisation benefits.

Man-made cellulosic fibres are an emerging option

Man-made cellulosic fibres are produced via the chemical processing of cellulose-based raw materials, such as wood pulp (Advances in Technical Nonwovens, 2016). They are a sustainable option due to their biodegradability and renewable sources. Global production of man-made cellulosic fibres (MMCFs) in 2022 was approximately six million tonnes, consisting mainly of 5.8 million tonnes of viscose and 0.3 million tonnes of lyocell (Textile Exchange, 2023). Viscose and lyocell fibres have been shown to be biodegradable under standard composting conditions (Sülar & Devrim, 2019). MMCFs are known for their soft feel, high absorbency, strength properties, and silk-like, shiny appearance. They are typically used in hygiene products: wipes, nappies/diapers, female hygiene products, filters, and medical textiles such as wound dressings (Advances in Technical Nonwovens, 2016). In nonwoven applications, viscose and lyocell are combined with cotton to enhance absorbency and comfort. They are also combined with pulp to increase wet strength (Weston, 2024). Several novel MMCFs are emerging, and some notable examples include Ioncell®, Norratex®, Biocelsol®, Spinnova®, Bio2™Textile fibre, and Kuura®.

Biopolymers can minimise plastic pollution

Biopolymers are another group of polymers that have the potential to revolutionise the nonwovens sector due their biodegradability and renewable sources as well as their thermoprocessable nature which means that they can be processed using similar methods as conventional fossil-based polymers. Polylactic acid (PLA) is the leading commercially available biopolymer. PLA's estimated production capacity is more than 250,000 tonnes and it is projected to continue to grow in the near future (Textile Exchange, 2023; Skoczinski et al., 2023). PLA can be obtained from the fermentation of sugars derived from plant sources such as corn, wheat, rice, and sugar cane (Tronci & Russell, 2022; Santos et al., 2021). PLA is biodegradable (it can be broken down by microbes) under certain conditions such as standard industrial composting or anaerobic digestion conditions (Skoczinski et al., 2023). Thus, the use of PLA in nonwovens has the potential to enhance the reduction of plastic pollution. PLA is noted for its low toxicity, low water absorption capacity, and melting point (Tronci & Russell, 2022). It has been used in disposable hygiene and protective products such as nappies/diapers, female hygiene products, wipes, surgical masks, and drapes, as well as in mulch mattings, air filters, and tea bags (as binder fibres) (Tronci & Russell, 2022).

PHAs (polyhydroxyalkanoates) are another type of emerging biopolymers, obtained from the microbial digestion of carbon-rich food crops and residues (Rosenboom et al., 2022). PHAs are noted for their readily biodegradable nature in various environments such as compost, soil, and marine (Rudnik, 2013). As a result, the use of PHAs has the potential to help minimise plastic pollution and dependence on fossil-based resources. This makes PHAs an attractive raw material option, especially in single-use applications such as disposable tableware and food packaging. Despite these attractive attributes, the use of PHAs has been limited due to the brittleness of the polymer during processing, degradation at high temperatures, high cost which is significantly higher than that of traditional fossil-based and other biodegradable polymers, and low yield during production, as well as odour issues which require the use of additives (Tronci & Russell, 2022; Rosenboom et al., 2022; García-Quiles et al., 2019).

Other interesting biopolymers include partially bio-based polymers such as polyethene terephthalate (bio-PET), polyethene (bio-PE), and polypropylene (bio-PP), which are still in their early commercial stages. A notable member of this group, bioPET, had a global textile fibre production of 6,300 tonnes in 2022 (Textile Exchange, 2023). These polymers typically contain roughly 25–30% bio-based content and 70–75% fossil-based petroleum-based polymers (Textile Exchange, 2022). While partially bio-based polymers are not fully biodegradable due to their fossil-based composition, they have the potential to reduce dependence on fossil-based resources and may lower carbon footprint (Rosenboom et al., 2022). Their bio-based content is usually obtained from renewable plant-based materials such as agricultural waste, corn, sugar cane, wood, and vegetable oil residue (Textile Exchange, 2022; Shogren et al., 2019).

Partially bio-based polymers also have the benefit of not requiring processes or technology modifications. They can be processed using technologies similar to their entirely fossil fuel-based conventional counterparts (PET, PE, and PP). Additionally, they can be recycled along with their fossil-based counterparts (Hann et al., 2020). Partially bio-based polymers can also be used in similar applications as traditional fossil-based polymers. However, because of their low availability and high cost compared to fossil-based materials, their use is limited (Hann et al., 2020). Given the potential benefits of partially bio-based polymers, it is essential to continue investing in the research and development of 100% bio-based materials.

New resources can be preserved with the use of recycled raw materials

Another approach to the development of sustainable nonwovens is the incorporation of recycled fibres and polymers. Recycled fibre are fibres obtained from post-consumer and post-industrial waste sources. The use of recycled fibres helps preserve resources, reduces landfill waste, and minimises the energy and resources needed for production of virgin materials (Kumartasli & Ozan, 2021). An important example of recycled fibres used in nonwovens is recycled polyester (rPET). Global fibre production of rPET was 8.6 million tonnes in 2022 (Textile Exchange, 2023). rPET fibres are mainly obtained from post-consumer PET bottles which account for 99% of all recycled polyester feedstock (Textile Exchange, 2023). rPET fibres have been used for needle-punched nonwovens in the construction and automobile sectors for roofing rolls, bonnet linings, carpet felts, sound, and thermal insulation, as well as other applications such as filter products (EDANA, 2023; Freudenberg, n.d.; Saricam & Okur, 2018).

Post-consumer textiles are another interesting source of recycled fibres due to their ample availability. A good example of post-consumer textiles is mechanically recycled cotton whose global production in 2022 was 300,000 tonnes (Textile Exchange, 2023). One of the most common nonwoven applications of post-consumer textile-based recycled fibres is in acoustic and thermal insulation.

However, the use of textile-based recycled fibres has been limited due to their heterogeneous nature as well as the presence of dyes and finishings (European Environment Agency, n.d.). Other possible routes to obtaining post-consumer textiles such as recycled polyester include chemical and biological recycling. However, the development of these alternative technologies has been limited due to high cost, energy, and feedstock (Textile Exchange, 2023).

Takeaways: in the Field of Sustainable Fibres and Polymers, New Innovation Will Break Through!

Sustainable fibres and polymers provide an environmentally friendly alternative to fossil-based polymers and fibres used in the production of nonwovens. Currently, cellulose-based fibres seem to be the most viable option due to their wide availability and biodegradability. Other bio-based polymers are also becoming increasingly popular due to their thermoprocessability and renewable sources. As technology and innovation continue to advance, it is expected that even more sustainable materials will emerge, and more technologies will be developed to improve the properties and commercialisation of these materials.

Although the use of sustainable fibres and polymers for nonwovens is a step in the right direction, cost-effectiveness and scalability are issues that still need to be tackled. Additionally, there is a need to fully understand the sustainability of novel materials, and more research needs to be conducted in the area of life cycle assessments. Furthermore, raising consumer awareness about the advantages of sustainable nonwovens can boost the demand for these nonwoven products, thus promoting more research and investment in sustainable fibre technologies.

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3.2 Man-Made Cellulosic Fibres

Michael Hummel** & **Marjo Määttänen

This chapter provides an overview of fibres spun from cellulose, often referred to as man-made cellulosic fibres (MMCFs) or manufactured cellulosic fibres. To understand the importance and challenges of emerging fibre technologies, it is important to look at the history of MMCFs. Further, this chapter explains the basics of established MMCF spinning technologies and describes the principles of the emerging cellulosic fibre types.

Man-made materials dominate the production of nonwovens, accounting for as much as 99% of total output. Man-made fibres encompass three classes:

- Fibres made from natural polymers: foremost cellulose (viscose, lyocell, cupro)
- Fibres made from synthetic polymers: polyesters (PET, PTT, PLA), polyolefins (PE,PP), polyamide (nylon 6/6, nylon 6), acrylics (PAN)
- Fibres made from inorganic materials (glass, ceramics, carbon)

Compared to man-made fibres, natural fibres account for a relatively small proportion of the total nonwovens production, but they are important in a variety of both single use as well as durable products. In Europe, wood pulp accounts for about 18% by weight of total staple fibre nonwovens production (Tronci & Russell, 2022). Approximately 340 kt of wood pulp is used annually for nonwovens in Europe. Compared to regenerated cellulose fibres, wood pulp provides a low-cost alternative. Due to the very short fibre length (<5mm), wood pulp is blended with man-made fibres for the production of nonwoven fabrics. Wood pulp is an important feedstock in both short fibre airlaying (specifically fluff pulp) and wetlaying systems, where the pulp is normally blended with short-cut man-made fibres. For airlaid nonwovens, fluff pulp made from softwoods containing long tracheid fibres (2–5mm) as well as shorter fibres is used for the voluminous absorbent cores of various single use hygiene products (e.g., nappies/diapers, adults' napkins, and incontinence management products). (Tronci & Russell, 2022).

History of Man-Made Cellulosic Fibres

The evolution of man-made cellulosic fibres (MMCFs) started in the late 19th century and has undergone a series of development steps (Liebert, 2010). Essentially, cellulose fibre preparation can be categorised within four main discoveries (Hummel et al., 2018).

- In 1846, Christian Friedrich Schönbein described the preparation of nitrocellulose, the first **organo-soluble cellulose** derivative. English physicist and chemist Joseph Swan and later Frenchman Count Louis-Marie-Hilaire Bernigaud, Comte de Chardonnet, developed the de-nitration to arrive at the first artificial cellulose fibres. (Richard, 2006; Chardonnet, 1884). The permanent or temporary chemical modification of cellulose to produce organo-soluble derivatives for further processing is the most important production route for MMCFs to date.
- The second strategy to form continuous cellulose filaments is based on the solubilisation of cellulose in **aqueous solvent systems**. Only a decade after Schönbein's discovery, Eduard Schweizer introduced Cuoxam as cellulose solvent, which formed the foundation for the development of a broad spectrum of aqueous systems for cellulose processing (Schweizer, 1857).
- The third route of MMCF production via so called direct solvents emerged in 1934 when Charles Gränacher filed a patent describing a class of organic solvents that were capable of dissolving cellulose without derivatisation or additional solubilisation-mediator. (Graenacher, 1934).
- Recently, a fourth approach to the formation of continuous cellulose filaments was pursued through processing of a suspension of various celluloses (wood pulp (Salmela et al., 2013; Salmela et al., 2015), cellulose nano fibrils (Håkansson et al., 2014)), with and without the use of binder substances to form a yarn-like structure.

Viscose Process

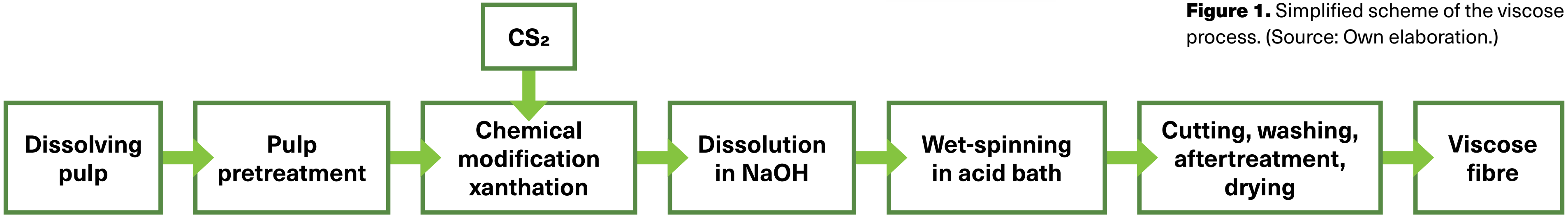

Figure 1. Simplified scheme of the viscose process. (Source: Own elaboration.)

MMCF production through intermediate cellulose derivatives is the oldest and currently most important technique. In 1892, British chemists Charles Cross, Edward Bevan, and Clayton Beadle, laid the foundation for the viscose process when they filed a patent describing the dissolution and regeneration of cotton and wood cellulose as cellulose xanthate (Cross et al., 1892). In the viscose process, cellulose is first activated in NaOH solution before it is derivatised with carbon disulfide (CS2). The respective derivative is called cellulose xanthate which is soluble in caustic solution. The resulting solution (called spin dope) is then wet-spun into an acidic spin bath. The acid, typically sulphuric acid, neutralises the caustic solution, causing coagulation of the cellulose xanthate. Simultaneously, the xanthate is saponified in the acid environment, that is, CS2 is released, and pure cellulose is regenerated. The complex interplay of these physico-chemical events requires a thorough understanding of the process, but also provides several opportunities for diversification.

Various improvements in the preparation of the spinning dope and in particular in the composition of the regeneration bath have led to significant developments which provided a wide spectrum of viscose fibres ranging from the standard cotton-like modal and polynosic fibres (high wet-modulus) to high tenacity and modulus technical fibres such as tire cord. However, the use of large amounts of CS2 is raising more and more concerns. CS2 is classified as toxic with concentrations of 500–3000 mg/m3 causing acute and subacute poisoning with a set of mostly neurological and psychiatric symptoms. In addition, sulphur-containing side products emerging during the viscose process are also a threat to humans and the environment. Strict environmental regulation in Europe and the United States has indeed resulted in the first stagnation of the earlier, continuously growing viscose production of the 1990s. Yet, new installations in China, Indonesia, and India, and optimisation of existing plants allowed viscose to remain the indisputable leader on the MMCF market with a production volume of 5.3 million tonnes in 2023 (The Fiber Year 2023, 2023).

Cuproammonium Process – The Second Way to Process Cellulose

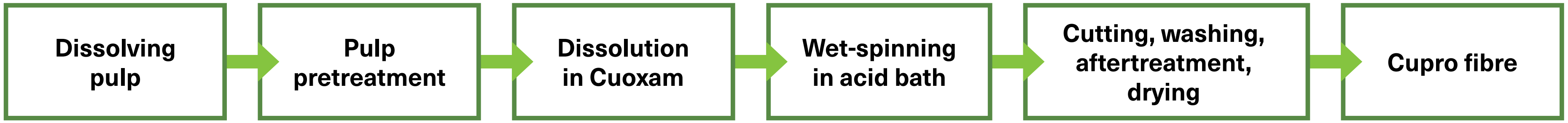

Figure 2. Simplified scheme of the cupro process. (Source: Own eloboration)

The second route for processing cellulose is based on the dissolution of cellulose in aqueous systems using solvation-mediators. Based on the earlier mentioned discovery of Schweizer, already in 1890 a spinning process using a copper-based complexing agent was developed by the French Chemist, Louis-Henri Despeissis (Despeissis, 1890), and later improved to produce MMCFs for textile applications (Fremerey & Urban, 1899a; Fremerey & Urban, 1899b). Today, cupro fibre, also known under the tradename BembergTM fibre, is produced on a scale of ca. 25 kt per year. Another subclass of aqueous cellulose solvents is formed by alkaline systems. Within limits regarding the maximum degree of polymerisation (DP), cellulose can be dissolved directly in sodium hydroxide solutions. Typically, cellulose must be activated in a pretreatment step such as steam pretreatment proposed by Kamide et al. (Kamida et al., 1984; Kamide et al., 1992; Yamashiki et al., 1992). The solubility of cellulose in alkaline systems can be enhanced by additives such as ZnO or urea (Cai et al., 2007; Xiong et al., 2014).

Lyocell Process – For Solvent-Spun Fibres

Figure 3. Simplified scheme of the NMMO-Lyocell process (NMMO.MH: N-methylmorpholine N-oxide monohydrate). (Source: Own eloboration)

The third type of cellulose dissolution and processing evolved with the discovery of *N*-methylmorpholine *N*-oxide (NMMO) monohydrate as a **non-aqueous**, **non-derivatising solvent for cellulose** (Johnson, 1969). NMMO monohydrate allowed for the direct dissolution of cellulose to prepare spin dopes that could be dry-jet wet spun into an aqueous coagulation bath (Fink et al., 2001). This technique is today known as the Lyocell process, a generic name which is derived from the Greek word *lyein* (meaning dissolve) and *cell* from cellulose and which is recognised by BISFA (International Bureau for the Standardization of Rayon and Synthetic Fibres, Brussels), and the Federal Trade Commission (USA) for solvent-spun fibres (BISFA, 2009). Lenzing AG, the largest manufacturer of Lyocell staple fibres, produces annually ca. 400,000 tonnes under their tradename Tencel®. Grasim Industries (Birla group), Sateri (RGE group), Hubei Golden Ring (China), and Kara Holding (Türkiye) are currently investing in lyocell production plants. The total NMMO-based lyocell fibre market volume is thus expected to grow quickly over the coming years. (The Fibre Year 2023, 2023).

Emerging Man-Made Cellulose Fibre Technologies – The Search for More Sustainable Options

Despite the unparalleled property spectrum and application portfolio of viscose fibres, the many environmental concerns associated with the extensive use of carbon disulfide outlined above promoted the development of alternative fibre spinning technologies for textile and technical applications. In recent years, new fibre types have emerged in each of the below mentioned four categories.

Intermediate Cellulose Derivatisation

In order to bypass the problems associated with the extensive use of carbon disulfide, alternative intermediate cellulose derivatives were explored (Schleicher & Fink, 1994). In the early 1980s, Neste Oy developed the viscose-like carbamate process which avoided the toxic sulphurous compounds (Huttunen et al., 1982; Ekman et al., 1984). Instead of using CS2, cellulose is derivatised with urea, a natural, harmless compound, to produce cellulose carbamate. The carbamate is also soluble in caustic solution and the resulting spin dope is wet-spun into an acidic or alkaline spin bath. (Nuopponen et al., 2023; Siren et al., 2023). The cellulose carbamate can subsequently be dissolved in NaOH(aq.) and is, in contrast to cellulose xanthate, a stable derivative which therefore facilitates a safer process to handle. Most unit operations are similar to the viscose process. This offers the possibility to adapt existing viscose spinning mills with reasonable effort to the carbamate process. Fink and co-workers at the Fraunhofer Institutes (Germany) have contributed significantly to the development, trying to meet the quality of regular viscose fibres and possibly surpass it to be able to compete with modal or other enhanced viscose products (Loth et al., 2003; Fink et al., 2014). Currently, the Infinited Fiber Company is adapting this technology (Valta et al., 2006) to produce MMCFs from textile waste. At InfinnaTM (Harlin, 2019; Paunonen et al., 2019; Määttänen et al., 2021), other recycled feedstocks such as paper and board have also been used for the preparation of the cellulose carbamate fibres (Asikainen et al., 2013).

New fibre-producers are adopting the cellulose derivatisation technique and achieving great business success.

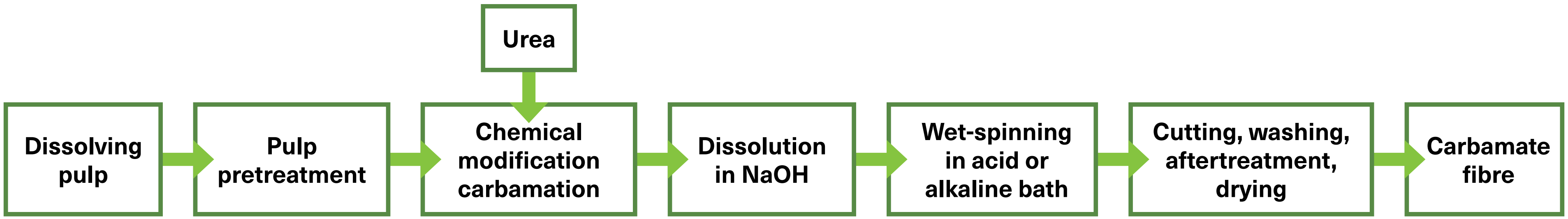

Figure 4. Simplified scheme of the carbamate process. (Source: Own eloboration)

Aqueous Solution Media

The direct dissolution of cellulose in aqueous NaOH solutions represents a promising green approach towards sustainable MMCFs, minimising the amount of chemicals. Challenges in the dissolution are addressed in the Biocelsol through a (mechano-) enzymatic pretreatment. (Ciechanska et al., 2001; Vehviläinen et al., 2008; Gronqvist et al., 2015). The enzymatic treatment increases the porosity of the pulp and decreases the degree of polymerisation of cellulose. The most effective results have been achieved with a continuous treatment using a twin-screw extruder after which the enzyme-activated pulp is dissolved in cold sodium zincate. Thereafter, the cellulose is dissolved directly in a NaOH solution without chemical derivatisation. The spin dope is spun into an acidic spin bath where the coagulation of cellulose is triggered through the rapid pH change.

Did you know that one benefit of Biocelsol fibres is that they don't require post-bleaching if the initial raw-material is white? (Vehviläinen, 2020)

Another company pursuing this avenue with a process comprising an alkaline coagulation bath is TreeToTextile. As feedstock, waste and side streams can also be used, including recycled paper and recycled cellulosic or cotton-polyester blend textiles. (Vehviläinen 2018, Stigsson, 2020). One benefit of these technologies is that they enable the utilisation of the existing viscose process machinery for the dope handling and fibre spinning.

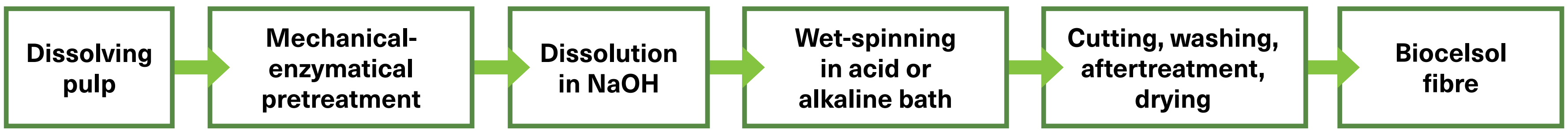

Figure 5. Simplified scheme of the Biocelsol process. (Source: Own eloboration)

Direct Cellulose Dissolution in Organic Solvents

NMMO, the solvent used in the commercial Lyocell process, suffers from some intrinsic shortcomings resulting from the redox-active N-O moiety and the thermally labile cyclic ether structure. This limits the versatility regarding more complex solutes such as functionalised polymers, but in particular it necessitates stabilisers to prevent so-called thermal runaway reactions. (Buijtenhuijs et al., 1986; Kalt et al., 1995; Wendler et al., 2009). An extensive overview of the side reactions and by-product formation in NMMO-cellulose solutions has been provided by Rosenau et al. (2001)[40]. Thus, despite the indisputable success of NMMO as spinning solvent, alternative direct cellulose solvents that bypass aforementioned NMMO-immanent problems would be highly attractive from an environmental and economic point of view.

Ionic liquids (ILs) – although known for many decades (Wakden, 1914) – represent a rather young substance class of cellulose solvents which have been investigated intensively during the last 15 years, since Rogers and his co-workers rediscovered the capability of selected ILs to dissolve cellulose and proposed lyocell-type fibre spinning (Swatloski et al., 2002; Swatloski et al., 2003). During the past decade, numerous studies have investigated spinning of different cellulosic solutes in various, almost exclusively imidazolium-based ILs (Hummel et al., 2015).

Ionic liquids (ILs) are a young substance class of cellulose solvents. At present, there are a few initiatives attempting to commercialise IL-based fibres.

The German Institutes of Textile and Fiber Research have developed the HighPerCell® process which uses [emim] octanoate (Vocht et al., 2021) to dissolve raw materials such as cellulose pulp, cellulose/chitin, or hemp pulp. A collaboration with the Austrian company proionic has been announced. In addition to these, the company HeiQ has launched a fibre under the tradename AeoniQ™. Presumably IL-based, little has been disclosed about the technology so far.

In 2022, Aalto University and the company Ioncell Oy (Finland) have started production of Ioncell® fibres on a small pilot-plant scale. Superbase-based ILs such as 1,5-diazabicyclo[4.3.0]non-5-ene-1-ium acetate, 8-diazabicyclo[5.4.0]undec-7-enium acetate, and 7-methyl-1,5,7-triazabicyclo[4.4.0]dec-5-enium acetate are used to produce textile and technical fibres from dissolving-grade pulp and waste textiles (Elsayed et al., 2021). The thus far biggest operations have been run by Metsä Group in cooperation with ITOCHU. Using paper-grade pulp as substrate, their resulting textile-grade fibre is called Kuura®. Production at an industrial pilot plant with an annual production capacity of about 500 tonnes has started in 2020. However, in 2023, the partners announced a change in the chemistry involved in their process.

Dissolution-Free Preparation (of Continuous Cellulose Filaments)

Founded in 2014, Spinnova has introduced an entirely new technique to produce cellulosic yarns for textile and technical applications. An aqueous suspension of long fibres such as softwood pulp is extruded through a tailored nozzle at elevated pressure. The fibres are aligned in a flow channel and then dewatered under pressure and twisting. Additives like alginate, pectin, or carrageenan, and divalent cations, are used to crosslink the individual fibres to create a rigid structure that is stable under rewetting. (Liukkonen et al., 2016). This approach is unique because it does not require any dissolution media and preserves the cellulose I structure. Meanwhile, alternative feedstocks have also been explored, including recycled textiles and agricultural by-products like wheat and barley straw.

BUSINESS OPPORTUNITIES LAY AHEAD!

The fibre types explored in this chapter are just some examples of many different emerging technologies entering the market. Most of them are being developed for textile applications in woven or knitted products but more and more are also considered for nonwoven applications. Their success in the nonwovens industry will be dependent on process compatibility, their cost, volume of supply, and their physical properties. (Tronci & Russell, 2022)

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3.3 Bonding Strategies for Nonwovens

Sara Paunonen

Designing a bonding strategy for the fibres making a web is a critical part of nonwoven manufacturing. The bonding process either boosts or fully creates the strength of the nonwoven web. Bonding can be based on mechanical, chemical, or thermal methods. This chapter discusses options to apply sustainability within these bonding options.

Did you know that, currently, the overall use of synthetic materials in the nonwoven manufacture is about 66%? (EDANA, 2017)

Currently, the overall use of synthetic materials in the nonwoven manufacture is about 66% which includes both binder materials and raw material fibres. The desirability of synthetics is now declining. The EU's Single-Use Plastics (SUP) Directive, launched in 2018, aims at reducing plastic pollution in the environment (see Chapter 2.2). This strongly drives the industries towards sustainability. Many nonwoven products such as single-use wipes and hygiene products fall under this directive.

> *Trend: The desirability of synthetics is declining.*

The change is driven also by consumers' growing awareness of environmental issues. However, the bonding solution is a rather invisible aspect of a product. It is thus challenging to draw consumers' attention to it, and therefore monetise it. For a nonwoven producer, the biggest influencers are usually their own customers (EDANA, 2017).

Mechanical Bonding – An Environmentally Friendly Process

In mechanical bonding, the action of water jets (hydroentanglement) or needles (needle punching) through the nonwoven web entangles the fibres and creates material strength. Some of the biggest segments of nonwovens use this type of bonding. As no additives are used, it is an environmentally friendly process.

Chemical Bonding – Tailoring Properties of Nonwovens with Altering Binders

Principle

In chemical bonding, a chemical such as a water-borne acrylic dispersion binder is applied by spraying, immersion, or with foam onto the nonwoven. Upon heating, the binder polymer gets dried and cured, and creates the desired strength, flexibility, and other properties to the substrate nonwoven. To achieve strong bonding, the binder polymer and substrate fibres must contain mutually reactive chemical groups.

Moving Towards Bio-Based or Biodegradable Binders

The interest towards bio-based and/or biodegradable binders is extensive and urgent. However, their development and deployment are gradual and challenging tasks.

From the nonwoven producer's point of view, the main challenge tends to lie in the availability of suitable sustainable binders on the market. The price of the binder, its performance at production line, alignment with end product-requirements, and the general pay-off need to be sufficient to make the transition. Extensive testing and even participation in development are often necessary.

From the binder producer's point of view, raw material availability in large-enough quantities, stable raw material quality, processability and convertibility, market size for the product, and existing supply chains are some of the challenges. Therefore, a common tactic is to substitute a part of the conventional binder formulation with bio-based content. The bio-content is commonly converted from side streams and waste from, e.g., the food or wood industries, such as wood bark and biomass, to substitute fossil raw materials.

Through this strategy of partial bio-based content, the risks and challenges can be mitigated and gradual transition of a company's current product into a bio-containing product is possible. A completely new product concepts is also possible but takes time, resources, and intensive development and upscaling efforts. There is widespread R&D activity on sustainable binder development both in the academia, research organizations, and companies.

Water-Borne Binder Chemicals

A nonwoven binder chemical is commonly a water-based formulation of various components. In addition to the binder base polymer itself, there are surfactants, cross-linkers, defoamers, pH control agents, etc. in the binder product. The base polymer in conventional nonwoven binders is usually an acrylate or vinyl polymer. The polymer is dispersed in a water medium to make the binder as a dispersions or emulsion. The number of bio-containing and fully bio-based applications currently on the market is small but growing.

To prepare bio-based binders, feedstocks for an adhesive polymer are sought from crop by-products, such as straw or husks, or various waste and side streams from industrial production such as papermaking or food processing. The choice of the polymer affects all properties of the nonwoven, including recyclability and degradability. Table 1 introduces a few plant and wood components that are being researched as relevant raw materials to be used in bio-containing binder formulations.

Table 1. Examples of intensively researched polymers from wood for binder production (Santos et al., 2021)

Polymer	Description
Cellulose	Several cellulose derivatives such as cellulose acetate, carboxymethyl cellulose, or ethyl cellulose can act as binders.
Lignin	Amorphous, thermoplastic, cross-linked phenolic 3D polymer. Needs to be modified for binder applications. Dark colour.
Starch	Natural binder. Used in early nonwovens but becoming interesting again. Used in native and modified form as dispersion or polymer solution. Starch derivatives make up 65% of all natural adhesives are used today.
Tannin	Focusing on substituting phenol-formaldehyde resins used in wood glues. Only condensed (non-hydrolyzable) tannins have a sufficient chemical reactivity to be developed as binders or adhesives

Hydrogen Bonding

Hydrogen bonding is a special bonding type. When humidity, temperature and pressure are applied to the web, cellulosic fibres in the web are naturally able to bond together. This type of bonding is familiar from the production of paper. It is truly sustainable, as it does not involve the use of any chemicals. However, as the material strength remains limited, the use of hydrogen bonding is limited mainly to absorbent core materials in nonwoven hygiene products.

Thermal Bonding –Shifting from Fossil-Based to Bio-Based Thermoplastics

Principle

Thermal bonding involves the use of thermoplastic fibres or powders. Common polymers include polyester, polypropylene (PP), and polyethylene (PE). Bonding is achieved by heating the polymer above its softening and melting temperature. Upon cooling, the polymer binds to itself and to the constituent fibres.

Poly(ethylene terephthalate)

Polyester, in particular poly(ethylene terephthalate) (PET) is the single most important raw material for nonwovens globally.

PET accounted for 25.5% of the total consumption (fibres, polymers, and binders) in nonwovens in 2022 (EDANA, n.d.). It is a thermoplastic polymer that is the biggest raw material for fibre-based nonwovens and second biggest for polymer-laid nonwovens. Recycled polyester from bottles covers 35% of polyester staple fibre consumption.

Currently, it is not possible to produce 100% bio-based PET in large industrial scale (Textile Exchange, 2022). Bio-based ethylene (to produce monoethylene glycol, MEG) is on the market (Ethanol Producer Magazine, 2023), but the other component, bio-based terephthalic acid needed for polymerisation, is not available. As a so-called drop-in polymer, 100% bio-based PET would behave as virgin petroleum-based PET.

Moving Towards Bio-Based or Biodegradable Thermoplastics

Thermoplastic bio-based polymers are being developed towards bio-based and biodegradable binder fibre applications. Bio-based monomers are derived from renewable, organic sources such as corn starch or sugar cane. Table 2 shows relevant biopolymers for binder fibre production. PLA is the only well-established biopolymer on the market, the rest are promising but considerably smaller-scale emerging polymers.

These novel biopolymers can be processed into monocomponent or bicomponent (bico) binder fibres. In bico fibres, only the fibre surface acts as a binder, whereas fibre core contributes to strength. Bico fibres were launched to the market already in the 1960s (Zhu et al., 2021) and are still a source of innovation. As an example of novel binder fibres, PLA/coPLA bico fibres are being produced by Trevira (Germany) and Tianjing (China).

Table 2. Examples of bio-based binder fibres for nonwovens

Polymer	Description
Bio-PE	Bio-polyethylene. Drop-in biopolymer made from biomass. Not biodegradable.
Bio-PET	Drop-in bio-based PET fibre that is expected gradually to gain market share. Not biodegradable.
PLA	Polylactic Acid (PLA). A polyester produced by microbial fermentation from sugars (starch). An established commercial biopolymer on the market. Biodegrades under specific conditions.
PHA	Polyhydroxyalkanoates (PHA) are produced from the bacterial fermentation of several carbon sources, particularly vegetable oils (soybean oil and palm oil). PHAs are a family of natural and biodegradable polyesters. Approaching to be used as textile and binder fibre. Easily biodegradable.

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3.4 Increasing the Potential of Cellulosic Nonwovens

***Ali Tarhini*, *Esubalew Kasaw Gebeyehu*,**
Tonmoy Saha* & *Ali Tehrani

This chapter explores the methods needed to functionalise cellulosic nonwovens. It focuses on improving the hydrophobic and antimicrobial properties of cellulosic nonwovens using sustainable and bio-based agents which will increase the potential of using these nonwovens in many new industries.

Nonwovens play a crucial role in various aspects of human life. The development of functional nonwovens involves incorporating advanced technologies, innovative materials, and smart design to address specific needs and challenges in various industries and aspects of daily life. The application areas of functional nonwovens are diverse, ranging from medical textiles to industrial fabrics, agricultural textiles, building and geotextiles, transport textiles, and even specialised textiles used in space exploration (Khan et al., 2022; Xing et al., 2022). Nonwovens are engineered to serve specific functions, for example, absorbency, liquid repellency, bacterial barrier, sterility, softness, strength, and thermal insulation.

Cellulosic nonwovens are becoming widely used in the nonwovens industry due to their excellent properties of biodegradability and renewability.

Cellulosic nonwovens are becoming widely used in the nonwovens industry due to their excellent properties of biodegradability and renewability Ma et al., 2017. However, these nonwovens are highly moisture absorbent and can absorb a large amount of water or other polar solvents (D.Knittel, 2009; Ma et al., 2017) which hinders their use from a wide area of applications like rain cloths, packaging, surgical gowns and coveralls, wound cover, sanitary towels, nappies/diapers, facemasks, industrial air filtration, geotextiles, chemical protection, and other related fields. Enhancing cellulosic nonwovens through functionalisation is key to improving their performance and tailoring them for use in such applications. By incorporating functionalities such as water repellency and antibacterial attributes, these nonwovens can meet the diverse requirements of casual wear for specialised applications in healthcare, outdoor activities, and technical applications. The healthcare sector alone demonstrates a huge demand for nonwovens. By 2023, the market value of antimicrobial textiles in healthcare is expected to increase up to 15 billion USD (Kiran Pulidindi, 2022).

WHAT A BUSINESS OPPORTUNITY:

The healthcare sector alone demonstrates a huge demand for nonwovens. By 2023, the market value of antimicrobial textiles in healthcare is expected to increase up to 15 billion USD.

Methods Used to Functionalise Cellulosic Nonwovens

Cellulosic nonwovens are very hydrophilic by nature due to a few primary reasons:

Firstly,

the fibres contain excessive hydroxyl groups which are hydrophilic and promote water absorption. The capillary action fibres also increase the absorption of water in fibre surface.

Secondly,

the creation of macro-porous surfaces during the manufacturing process of these nonwovens permits water to seep through upon contact. The development of hydrophobic nonwovens focuses on countering these issues by either altering the surface energy or surface roughness of the nonwoven through incorporation of hydrophobic agents.

Cellulosic structure not only promotes water absorbance but also creates a moist environment ideal for microbial growth, as cellulose serves as a nutrient source, which leads to material degradation and causes harmful microbial diseases for the user. Hydrophobic and antimicrobial treatments are achieved through the incorporation of hydrophobic and antimicrobial agents (Tables 1 and 2) at various stages of production processes, including adding functional agents to the dope solution during fibre spinning stage (Morais et al., 2016), mixing them with the binder in the nonwoven manufacturing stage, or applying post-treatment methods such as polymerisation, dip coating, layer-by-layer coating, spray coating, grafting, and plasma processing (Tehrani-Bagha, 2019; Wei et al., 2020). The most popular methods of applying these agents onto the nonwoven is pad-dry-cure method (Gorade et al., 2021). It involves passing of a fabric through the solution and between rollers where they pick up the chemicals at certain pressure, speed, and time. Later, they dry and cure the fabric at higher temperature for permanent fixation of agents onto the fabric.

Hydrophobisation of Cellulosic Nonwovens

Commercial Agents for Hydrophobisation

The process of chemically finishing fabrics to make them hydrophobic involves applying specific chemicals to repel water. Currently, there are various processes and chemicals available in the market for hydrophobising fabric, as shown in Table 1. However, finding the right balance between efficiency, quality, cost, and sustainability remains a challenge. The earliest method to make fabric hydrophobic was using water-repellent paraffin emulsions to cover fibre pores, yarns, and fabric structures with a mechanical coating (Abo-Shosha et al., 2008; Mohamed et al., 2017). While cost-effective, this technique is limited due to its rigidity and lack of durability. Coating hydrophilic substrates with polyvinyl chloride, rubber, and polyurethane provides durable finishes, but it comes with downsides like stiffness and poor breathability (Holmes, 2000; Lomax, 1985). Chemically, polyurethanes are polymers made by reacting diisocyanate with polyol. However, not only are diisocyanates associated with several adverse health effects, they are also associated with irritancy.

For enhanced hydrophobicity and forming a repellent layer on cellulose, industries are using silicone and fluorocarbon-based compounds (Li et al., 2019). Silicon-based compounds are less toxic and less persistent than long-chain fluorocarbons, yet they are reported as genotoxic. Furthermore, residual baths and effluent from these finish application techniques are toxic to aquatic life (Williams, 2017). Fluorocarbons give the lowest surface free energy among all hydrophobic finishes available on the market (Li et al., 2019). However, their current registration as substances of very high concern by the European Chemical Agency is due to concerns about their toxicity, long-range mobility, and persistence. Since 2020, there are legal restrictions, particularly for Perfluorooctanoic acid (PFOA), under the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) framework for fluorocarbons under Annex XVII restriction in textiles sold in the European market. This includes a limit threshold for PFOA with a permissible level of less than 25 parts per billion (ppb). The ongoing consultation involves considering further restrictions on fluorocarbons, with some due to take effect in 2023. Despite the adverse effects, there is continued interest by manufacturers in using fluorocarbons in various applications like medical textiles, water treatment filtration, production processes, and effluent treatment. Replacing fluorocarbons with less harmful chemicals remains a challenge.

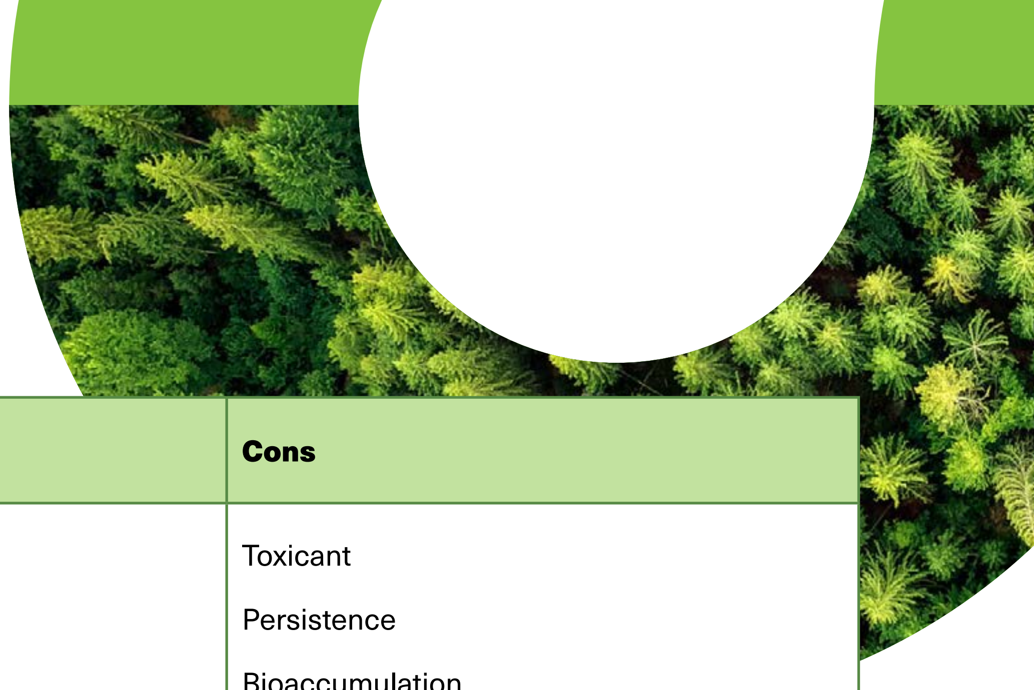

Table 1: Chemicals used to enhance hydrophobicity of textiles and nonwovens

Major Chemical Classes	**Pros**	**Cons**
Fluorochemicals	Very effective agent	Toxicant Persistence Bioaccumulation Long-range mobility
Silicones, aka Siloxanes	Less toxic and less persistent than long-chain PFAS (Polyfluorinated Substances)	Genotoxic
Hydrocarbons	Readily biodegradable Low toxicity	Least efficient Human carcinogen when mixed with melamine
Polyurethanes	Resistant to harsh environment	Respiratory issues Sensitisation Irritation

Bio-Based Agents for Hydrophobisation

Achieving the optimal hydrophobicity in cellulosic nonwovens while minimising the environmental footprint of the chemicals used is a crucial factor in the hydrophobisation process of cellulosic nonwovens.

Optimal hydrophobicity + minimising environmental footprint = CRUCIAL for further development!

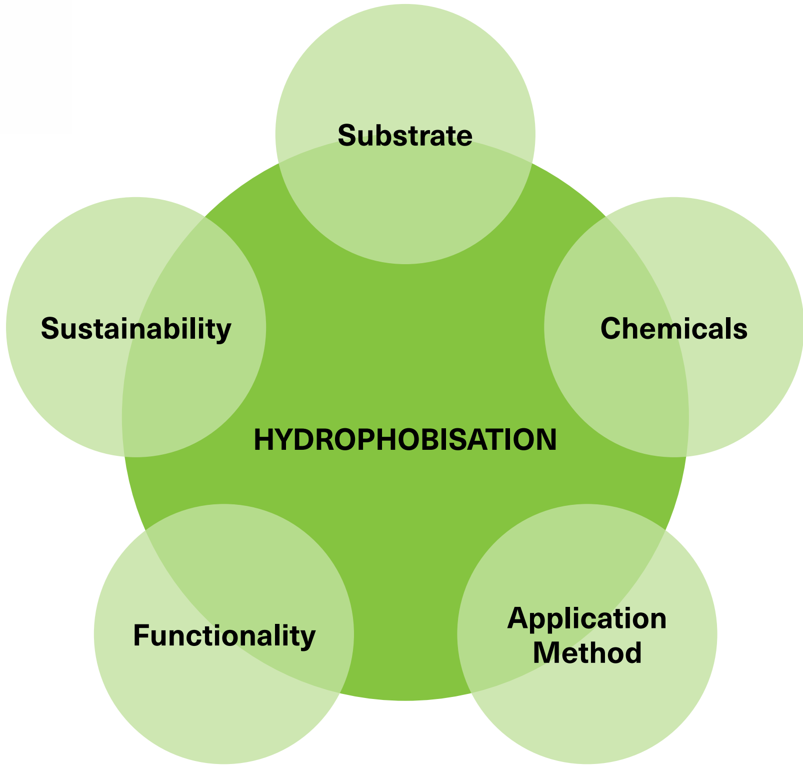

Figure 1: Different aspects of green hydrophobisation for cellulosic nonwovens

Figure 1 illustrates the factors involved in green hydrophobisation of nonwovens. To attain desired water repellency, it involves a systematic process that intertwines the knowledge of substrate characteristics, selection of eco-friendly chemicals, choice of application methods, and a commitment to broader sustainability goals to enhance water repellency, without sacrificing environmental integrity.

Using bio-derived materials such as plant extracts, oils, waxes, or other renewable resources, preserving environmentally friendly profiles, and compatibility with a more sustainable approach to textile hydrophobic finishing is the current area of interest. This method entails incorporating bio-based hydrophobic compounds into the fabric using a variety of application methods, resulting in fabrics with improved water repellency. The approach is netted to fulfil the increased demand in the textile/nonwovens sector for eco-friendly hydrophobic solutions, providing a greener alternative compared to conventional treatments.

Antimicrobial Properties of Cellulosic Nonwovens

Cellulosic nonwovens generally have a large surface area and are known to retain moisture well, which makes them ideal for the growth of microbes like fungi and bacteria. The growth of microbes on the material, in turn, results in several negative consequences for both the user and the material (Morais et al., 2016). Therefore, due to the growing public health awareness of the harmful effects of microorganisms, especially after the COVID-19 pandemic, the demand of antimicrobial nonwoven fabric is increasing progressively. Commercially produced synthetic antimicrobial agents such as triclosan, quaternary ammonium compounds, N-halamines, Polyhexamethylenebiguanide, and metal salts have been used for functionalising nonwovens over last few decades. (Periolatto et al., 2017). They have shown good efficacy against a broad spectrum of disease-causing microorganisms. However, when these synthetic agents leach out or get released into the environment in subsequent processes, they can be very detriment to the environment and to human health. For instance, it is reported that triclosan disrupts thyroid systems in rats and frogs (Zorrilla et al., 2009). A list of synthetic antimicrobial agents, their structure and adverse effects has been presented in Table 2.

Table 2: Synthetic antimicrobial agents and their limitations (Zain et al., 2018; Windker et al., 2013)

Synthetic Agents	Limitations
Triclosan	Sensitisation and skin irritation such as itching Exposure to sunlight causes the breakdown of triclosan & release toxic polychlorinated dioxins. High toxicity for aquatic organisms, which can cause long-term effects in the environment.
Metallic compounds	Cytotoxicity and genotoxicity Accumulation in organisms Antibiotic resistance
Quaternary Ammonium Compounds (QACs)	Difficulty of controlling the rate of diffusion The release of QACs from the fabrics into the environment could have destructive impacts on living organisms in water because they can affect susceptible bacteria.
Polyhexamethylene Biguanide (PHMB)	Toxic to the environment

As synthetic antimicrobial agents present a significant deal of concerns to the environment, researchers and producers are engaged in attempting to replace them with bio-based sources. For instance, chitosan has excellent antimicrobial properties against different bacteria, and it is gaining popularity in the commercial market (Li et al., 2021). Willow bark and nettle leaves are also a good natural source to replace these synthetic antimicrobial agents. They are rich in phenolic compounds, but only effective against gram-positive bacteria (Elez Garofulić et al., 2021; Aleman et al., 2023). Citrus fruit peels rich in naringenin have excellent antimicrobial properties against both gram positive and negative bacteria (Jp, 2000). However, extraction of antimicrobial agents from bio-based sources is often time consuming and depends on other factors, such as climate and atmosphere, availability, and mechanical sorting.

A FUTURE OUTLOOK:

As we are moving towards sustainable society, it is imperative to replace synthetic compounds with bio-based sources for functionalisation of nonwoven fabrics. Nature has abundant sources from which we can extract antimicrobial compounds, apply these on to cellulosic nonwovens in a convenient way, and thereby also meet the profound market demand of these products in a sustainable way.

WHAT IS REQUIRED?

Cellulosic nonwovens known for their breathability, renewability, and biodegradability need to be engineered for enhanced performance through hydrophobisation and antimicrobial activity, addressing the need for water repellency and antimicrobial activity in diverse applications.

However, achieving hydrophobicity and antimicrobial properties often involves complex processes and chemicals, raising concerns about environmental impact and health effect. In this response, there is a considerable effort to move towards adopting greener alternatives. The use of bio-based agents represents a vital shift towards reducing the ecological footprint of textile manufacturing while preserving the desired functional attributes. Within this context, initiatives by industries are at the forefront, driving the transition towards sustainable textile innovation by turning these eco-friendly concepts into reality.

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3.5
End-of-Life Options

Piia Kanto, Marita Hiipakka** & **Anna Garton

In this chapter we give a short introduction to nonwovens' end-of-life options. We also introduce a method used in the SUSTAFIT project for conducting disintegration testing for nonwovens. This is for you if you are interested to learn more about how to handle nonwovens in their end-of-life options.

The sustainability of materials and products is an important aspect today and it also applies to nonwoven fabrics. Raw materials are only one sustainability consideration, and more and more attention should be paid to the whole life cycle and circularity of products.

Did you know that according to the general guidelines, many nonwoven fabrics should be sorted into mixed waste?

According to the general guidelines, many nonwoven fabrics should be sorted into mixed waste. Depending on the material and the intended use, other end-of-life options could also be considered for nonwovens. One end-of-life option for these materials could be organic waste treatment if the materials as such cannot be kept in closed-loop recycling. Organic recovery of a material by composting is an important alternative for reducing and recycling of materials by biological means. From the circular economy point of view, the recycling of nonwovens should also be considered.

Composting – More Testing Needed

For composting purposes, the product's disintegration and biodegradability as well as chemical characterisation and ecotoxicity has to be tested. Compostable means that material can break down or fully degrade in a certain time and disintegrate into natural elements in a compost environment, leaving no toxicity in the soil. It should be noted that there is a difference between home composting and industrial composting. If the material is compostable in an industrial composting environment it doesn't mean it would be equally compostable in a home compost. The differences between these two are in the temperature and the time it takes material to disintegrate and biodegrade. (EU 2022; European Bioplastics 2009 and 2015).

Methods for Testing Biodegradation and Compostability

There are several protocols to test a material's compostability. The methods and standards for testing nonwovens discussed in this chapter are degradability, biodegradability, and compostability. Several different tests may be used. Some are standard methods, and some are so called in-house methods for which more detailed public information may not be available. Typically, the standard methods used for testing nonwoven fabrics are intended, for example, for plastics. Within this study, the information for the method and standard review was collected from scientific publications, company web pages, and directly from the companies. The examples of the standard methods used for testing nonwovens are presented in Table 1. The information in the table is based on the collected data, which is why the standards mentioned in the table are not necessarily always the latest versions, and why some standards are national.

Table 1. Examples of the standard methods used for testing degradation, biodegradation and compostability of nonwovens

Standard	**Name of the Standard**
ASTM D5338	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures
ASTM D5988-96	Standard test method for determining aerobic biodegradation in soil of plastic materials or residual plastic materials after composting
ASTM D6400	Standard Specification for Compostable Plastics
DIN EN 17033	Plastics—Biodegradable mulch films for use in agriculture and horticulture–Requirements and test methods
EN 13432	Requirements for packaging recoverable through composting and biodegradation
ISO 14855	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions. Method by analysis of evolved carbon dioxide. Part 1: General method (ISO 14855-1:2012)
ISO 16929	Plastics — Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test
ISO 17556:2003	Plastics—Determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved
ISO 846-1997	Plastics —Evaluation of the action of microorganisms
NF T 51-800	Plastics — Specifications for plastics suitable for home composting
NF U52-001	Biodegradable materials for use in agriculture and horticulture—Mulching products - Requirements and test methods
PN-EN 14045:2005	Packaging –Assessment of the decomposition of packaging materials in laboratory scale in compost conditions.
PN-EN 14806:2010	Packaging – Introductory assessment of the decomposition of packaging materials in laboratory scale in compost conditions.
PN-EN 2005	Plastics – Determination of the degree of disintegration of plastics materials under simulated composting conditions in a laboratory – scale test
ISO 20200:2023	Polymers – Estimation of polymer decomposition in laboratory scale in simulated compost conditions
EN 17427 - 2020	Packaging - Requirements and test scheme for carrier bags suitable for treatment in well-managed home composting installations
UNE-EN 13432	Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging
UNI 11462	Plastic materials biodegradable in soil – types, requirements, and test methods
ASTM D 6094-97	Standard guide to assess the compostability of environmentally degradable nonwoven fabrics (Withdrawn 2008)

Disintegration Testing as a Part of Studying Compostability

To better understand a material's suitability for composting purposes, laboratory-scale disintegration testing is needed to study the materials' physical breakdown into very small fragments in biological environment. As a part of the SUSTAFIT research project, disintegration tests were conducted on nonwovens according to the standard protocol ISO 20200:2015 Plastics: Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test. This standard has since been replaced by the standard ISO 20200:2023, but our project's tests series were completed using to the 2015 version of the standard. The laboratory scale testing was carried out by keeping the test materials buried in aerobic synthetic waste reactors (Figure 1) for at least 45 days in a constant temperature and specified conditions. After the test period, the mass of the remaining, non-disintegrated test materials was determined to give a degree of material disintegration, together with the compost and biowaste validity testing. This method does not determine the biodegradability of materials under composting conditions, and further testing is necessary before making claims about the material's compostability. In the SUSTAFIT research project, the method was found suitable for testing the disintegration on nonwoven materials in laboratory conditions.

Figure 1. The synthetic waste reactor (Kanto, 2023)

Other End-of-Life Options

Nonwovens are sorted according to waste management instructions into mixed waste, from where they end up being incinerated. From a circular economy point of view, it would be beneficial to consider options for recycling nonwovens instead of incinerating and composting them. The value of nonwoven fabrics is already very low, so the value of recovered, sorted, and processed recycled material is not necessarily very high, and it may be difficult to find the higher value applications for recycled nonwovens. On the other hand, it would be better to keep the material in circulation as long as possible, and retain incineration and composting as the last resorts. When it comes to recycling nonwovens, it is possible, but it requires solving a number of issues such as available volumes, composition, cleanliness, damage during use, as well as the production process. Nonwovens produced from a single material are easier to use than mixed or blends. Additionally, the recovery from waste streams is more complicated due to blending of different fibres and the use of additives during production, and therefore industrial side streams are an easier option to recycle. The fibre quality will suffer during multiple cycles if mechanically processed and adding recycled content as blends into nonwovens means creating multifibre products that are more difficult to circulate back into new products.

Currently, few or no nonwovens are sent to waste management facilities. Recycling would require an increase in the volume of recyclable nonwoven fabrics, which in turn would require the establishment of a nonwoven collection infrastructure. For recycling to be effective, the delivery of nonwovens to the collection should be as simple as possible for the consumer. A further issue to note is the material composition.

It is easier to recycle materials consisting of a single fibre type than recycling complex materials with different fibres or additives such as glues and fire retardants.

In addition, the cleanliness of the nonwoven fabric must be taken into account. Nonwoven fabrics are used for many different purposes, and some of these the materials get so soiled that their recycling would require extensive cleaning. Sanitary aspects should also be considered when nonwovens are used in hygiene or personal care products.

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3.6
Piloting as a Path to Sustainable Nonwovens

Sara Paunonen, Tiinamari Seppänen, Timo Rantanen & Antti Oksanen

This chapter discusses piloting as way to develop materials, and describes the piloting facilities for the production of nonwovens at VTT Technical Research Centre of Finland and Tampere University of Applied Sciences TAMK. This is for you if you want to learn more about the possibilities of scaling up the production of nonwovens to pilot-level.

Development of sustainable nonwovens covers experimenting with various raw materials (see Chapters 3.1 and 3.2), web formation and fibre bonding methods (Chapter 3.3), and fabric finishing techniques (Chapter 3.4) with the general goal of saving resources and environmental friendliness.

Experimentation typically occurs in stages that gradually scale the production towards full production. The goal is to detect and solve emerging problems step-by-step, and thus gain confidence that the solution has the potential to turn into a stable and viable product and that production can be carried out in a safe manner. Table 3 shows the generic stages of material development.

Table 3. Main stages of material development

Level	Description
Laboratory-scale	Small scale research, tests and verifications that consume minimal amounts of raw materials. The test environment is controlled. Provides insights into governing mechanisms and proof of performance.
Pilot-scale	Mimics full scale production, but at a lower cost and material consumption level. Possibility to extensively modify and monitor the production process and take samples from the process and product. Provides trust on the feasibility of the solution at full production.
Production-scale	Final tests before moving to full production. Carried out in real conditions. Any errors at this stage are costly.

In pilot-scale verifications, the focus is on experimenting with raw materials, unit processes and equipment that will correspond to an industrial installation. The goal is to provide sufficient data for decision making towards full production. The pilot process allows for investigations into versatile topics such as raw material handling, unit processes, space requirements, process operability and stability, waste stream handling, and achievable product quality, before large amounts of money have been committed to a larger production plant. For complex and completely new processes, even the pilot-scale is usually divided into several scale-up stages.

Laboratory-Scale Facilities at VTT and TAMK

Airlaying, Foamlaying, and Waterlaying at VTT

VTT's fibre materials technology platform allows for experimentation and development of new fibre-based material solutions for nonwovens, textiles, and other applications. The research infrastructure consists of laboratory-scale web forming apparatuses, two pilot lines, and supporting laboratory facilities. The infrastructure is located at VTT Jyväskylä in Finland.

Nonwoven hand-sheets can be prepared with the airlaying, foamlaying, and wetlaying methods with the laboratory-size moulds. The minimum material consumption is around 20 grams, and the size of the hand-sheet is A4. In the airlaid drum former, typical raw material is fluff pulp, textile fibres (3 mm to approx. 24 mm), or bi-component fibres. Wetlaid and foamlaid sheets can be prepared with the same mould from fibres having a fibre length from 3 mm to 12 mm (up to 20 mm).

Carding Machines at TAMK

Carding is a dry process that mechanically disentangles and mixes raw material fibres that have a length of over 30 mm. The fibres are fed between rotating cylinders that are covered with metal pins (Figure 1). This action aligns them to a continuous batt (web). The batt is bonded with needle punching (Figure 2), where barbed needles are punched vertically through the web to hook and entangle fibres.

The textile laboratory at TAMK in Tampere, Finland, has an Automatex carding device (Model MCA 500, Figure 1) and an Automatex needle punching device (Model MPR 600, Figure 2).

With these machines, various novel staple fibres (see Chapter 3.2) can be processed into carded webs. 25 grams to 50 grams of fibres is needed for one carding batch.

Figure 1. The pilot-scale carding device at TAMK

Figure 2. The needle-punching device at TAMK

Nonwoven Pilot Lines and Facilities at VTT

VTT SUORA – Wet and Foam Laying Pilot for Nonwovens, Paper, and Board

VTT SUORA (Figure 3) was originally designed for water-laying (paper and board making) but was later modified for foam laying. The principle of foam laying is similar to that of wetlaying. The difference is that the transfer media is aqueous foam instead of water. Fibre suspension contains typically 40% to 70% of air.

Figure 3. VTT SUORA pilot machine for wetlaids and foamlaids

Fibre suspension or fibre foam that is fed to the machine is made in the pulper by mixing water, fibres, and tentatively foaming agent. The maximum line speed of VTT SUORA is 2000 m/min (normal speeds 300–1,000 m/min), and the web width is 300 mm. A hydraulic Optiflow headbox is normally used for both water and foam laying.

The line includes forming and pressing sections. Depending on the desired method of web forming and water removal, the pilot can be run in Fourdrinier, hybrid, or gap mode. The line has a Symbelt single-nip press section. Drying is done offline in a 4-cylinder heater or at laboratory with a cylinder drying device.

VTT SUORA can be run either in loop or production mode. In loop mode, the formed web and the recovered process water (or foam) are returned back into the process. The production mode involves reeling the wet fibre web instead of recirculating it. During reeling, fresh fibres are being fed to the pulper. In both modes, the produced web can be sampled after the press section. A 30 kg amount of fibres is needed in the loop mode, and 300 kg when running in the production mode.

Stratified Forming

A special, 6-layer headbox allows for so-called stratified foam forming to be carried out with the VTT SUORA pilot machine. Stratified forming is simultaneous forming of a multi-layered sheet with one single headbox. In the forming process, raw material furnishes are kept separate as long as possible, until they join in the final product web as layers. With VTT SUORA, three different fibre furnishes can be fed to the headbox simultaneously.

Inclined Wire Headbox

An inclined wire headbox is a standard solution for the manufacturing of wetlaid nonwovens that are commonly used in various medical and health care, household, and industrial applications.

Both the wetlaying and foamlaying processes can employ the inclined headbox. Water or foam removal occurs mainly under the headbox lid. Thus, higher flow rates and lower consistencies can be used. The forming board is tilted to an angle to get more drainage.

The inclined wire headbox, installed in VTT SUORA in 2023, is 250 mm wide and allows 3-ply layering. The maximum flow rate is 70 L/s in a single layer structure. The control options include dewatering profile, position of the top plate, and wire angle to achieve the best forming results. The first 30 gsm to 60 gsm fibre webs were produced with a speed of 500 m/min.

VTT SAMPO – Foamlaying Pilot for Non-Pressed Webs

VTT SAMPO (Figure 4) was built in 2017 for detailed and advanced investigations into foam forming of porous and bulky materials. Various sustainable nonwovens, including technical textiles, commodity products, composites, and hybrid products, can be produced with VTT SAMPO from wood and natural fibres, staple fibres, filaments, and polymers.

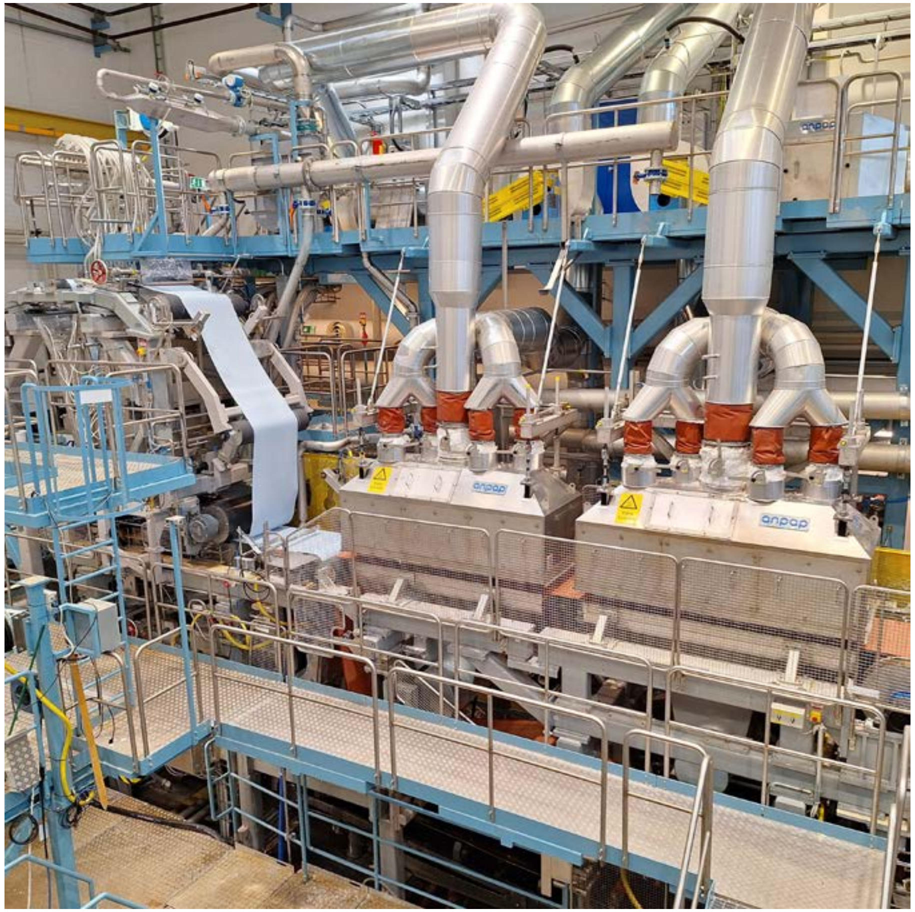

Figure 4. VTT SAMPO for foamlaying of non-pressed fibre webs

Sustainability is achieved by selecting bio-based or biodegradable raw materials and bonding methods for the nonwovens. The foam quality and machine run parameters are adjusted for each raw material and application to produce high-quality nonwoven webs.

The VTT SAMPO line consists of an approach system of raw materials and forming and drying sections, followed by a reeler. There is no pressing section after forming. The vertical headbox allows 3-layer stratified forming. The web width is 725 mm before edge trimming. The maximum machine speed is 1000 m/min, and normal speeds range from 25 m/min to 200 m/min. The drying section consists of impingement, through-air, and IR dryers (Figure 4).

VTT SAMPO shares the approach and process control systems with the neighbouring VTT SUORA. Therefore, only one of the machines can be run at a time. The raw material consumption is close to that of VTT SUORA. VTT SAMPO can be run in loop or production modes.

As an option, continuous web and dry particles can be fed into the headbox to create composites or nonwovens with gradient structures.

VTT SAMPO can be changed to fourdrinier mode, which is beneficial for the preparation of thick webs. In this flat wire mode, one wire loop equipped with a drying fabric is covering the forming and drying sections. The vertical headbox is bypassed and fibrous foam is pumped to the horizontal part of the forming section. Slow machine speeds can be used (0.5–5.0 m/min). With this geometry, it is possible to produce high grammage webs (500 gsm to 2000 gsm) or/and low-density structures (20 kg/m3 to 50 kg/m3).

VTT SUORA and SAMPO are operated with a Valmet DNA process control system. Over 500 online measurements (pressures, flow rates, temperatures, powers, speeds) are collected in the process data analysis and diagnostics tool Savcor Wedge. Special measurements include, e.g., online-formation to monitor web quality. The modular design of both pilot machines allows fast and easy process modifications and installations of sub-processes. Small scale testing without web forming is also possible (pumping, mixing, foaming, disintegration).

4.

BUILDING ECOSYSTEMS

The fourth section of the workbook, Building Ecosystems, explores how the nonwovens industry can benefit from collaborating with various operators such as service and test bed providers, as well as other stakeholders, to foster innovation and sustainability. In this section, we introduce the concept of service and test beds as platforms that enable the testing and validation of new nonwoven materials, technologies, and applications. This section presents some examples of existing test bed providers in Finland and elsewhere in Europe. We examine how digital platforms can facilitate the exchange of information, resources, and value among the nonwoven actors, and support the transition to more sustainable and circular practices. Additionally, we focus on the importance and strategies of engaging various actors in the nonwoven value network to create shared value and foster innovation, and describe how ideation can generate new ideas and solutions for the nonwovens industry, especially when focusing on more sustainable and circular solutions. The section concludes with examples of ideation methods and innovation tools, and discusses how they can be applied in the nonwovens industry.

4.1 Service and Test Bed Providers for Future Collaboration

Minna Varheenmaa & ***Taina Kamppuri***

This chapter details service providers in Europe and North America for sustainable nonwovens, focusing on testing and piloting services sourced from the members of EDANA and the Nonwoven Research Institute, as well as trade fairs. It categorises these services by common nonwoven technologies, briefly described using EDANA's resources.

Our aim was to map global testing, research, and piloting services for nonwoven applications that companies and research organizations provide for their customers and collaborative business partners. These companies are typically equipment providers, manufacturing companies, and commercial or non-commercial testing and research organizations as well as research units of technical universities and universities of applied sciences. However, it is quite common that services are only available to business partners working in close collaboration with the service provider. The close collaboration can be a common international project, or an acquisition of an equipment. However test assignment type acquisitions typically are available for any customer interested in, and in the need of, an impartial testing service. The biggest companies are often multinational organizations.

Nonwoven testing and piloting services were studied based on the information found on the company webpages of the members of EDANA and the Nonwoven Research Institute in Europe and North America. In addition to these, trade fairs Technical Textiles 2022 in Frankfurt, MiniExpo 2022 in Borås, and ITMA 2023 in Milano introduced some stakeholders active in the nonwovens industry. In Nordic and national projects concerning nonwovens from mechanically recycled fibres, closed loop test bed for textiles and textile value chain. steps were taken to prepare the textile industry towards recycling of textiles, circular economy, and digitalisation. National operators providing testing and piloting services on closed loop test bed for textiles were categorised and listed in a VTT report. This general description of the test bed system includes also web forming and binding of fibres for nonwovens. (Heikkilä, 2022; Heikkilä, 2020).

The service providers for pilots, research, and tests in Europe and in North America are presented in Table 1. The services are categorised based on the most common nonwoven technologies, and additionally whether the service provider is an equipment provider, microbial, or biodegradation test provider, and whether they are certified or not.

Brief Descriptions of the Main Nonwoven Technologies

Airlaying technology is for short fibres where an airstream helps to mix fibres to form a randomly oriented web on a moving belt (EDANA, n.d.).

In the **drylaying** method, opened and blended fibres are conveyed to a card by airstream. A carding machine combs the fibres into a web either parallel – in machine or cross direction – or in random order depending on the strength properties required in the end use product. The web is then consolidated using a suitable method determined by the fibre type used and end use purpose. (EDANA, n.d.).

The **wetlaying** method resembles the manufacturing of paper. A thin slurry of long fibre and water is laid on a moving wire screen where water is drained off and fibres form a web. The remaining water is removed from the web by pressing in between rollers and drying. The web can be impregnated with binders at a later stage. Strength properties are rather uniform in all directions of the planar web. (EDANA, n.d.).

In **spunmelting** technology, thermoplastic polymer chips are melted, and a nonwoven web is directly formed through a spunlaid or meltblown process, or as a combination of these methods. Molten polymer chips are extruded through spinneret, and the filaments are stretched and quenched before placing onto the conveyor belt for forming the web. The term spunbonded refers to thermobonded spunlaid. In the meltblown process, the filaments are attenuated by hot air streams instead of quenching. This helps to get finer filaments. Even finer fibres can be achieved with sub-micron spinning such as meltblown, centrifugal spinning, solution spinning, and electrospinning. (EDANA, n.d.).

Thermal bonding technologies include calendering, through-air in hot air stream, drum and blanket systems, or ultrasonic. The thermoplastic properties of fibres are exploited through either the fibres in the web, or through the addition of low melting fibres or bicomponent fibres into the web. Pressure binds the fibres into the web. (EDANA, n.d.).

A web can be consolidated through interlacing fibres mechanically, either by the **needlepunching** method using special needles, or by the **hydroentanglement** method (spunlace) using fine water jets of high-water pressure. The latter is often used for carded or wetlaid webs. (EDANA, n.d.).

In **chemical bonding**, a liquid-based chemical bonding agent is applied to the web. Application can be made by impregnation, coating, spraying, or intermittently, as in print bonding. (EDANA, n.d.).

A range of finishing treatments can be used for tailoring or functionalising the nonwoven for specific purposes. These include mechanical stretching, perforating, crimping, or changing the haptics or repellency properties by treating the fibre surface or the nonwoven chemically. (EDANA, n.d.).

Finally, the nonwoven roll goods are converted into a version closer to the final product by slitting, cutting, folding, sewing, or heat sealing. (EDANA, n.d.).

Table 1. Service providers for pilots, research, and tests in Europe and in North America (SB = spunbond, MB = meltblown, Slace = spunlace)

Equipm/ Technol	Research center	Testing	Piloting	Biodegrade-ability	Micro-biology	Certified	Carding	Airlaid	Drylaid	SB	MB	Submicron	Wetlaid	Slaced	Needle-punched	Thermo-bonded	Chemically bonded	Other	Company name	Country
E			x				x	x					x	x	x	x			ANDRITZ Laroche S.A.	France
E			x					x											Anpap Oy	Finland
T	x	x	x							x	x							Bioplastics for nonwovens	Biome Bioplastics	UK
		x																	BRACHI TESTING SERVICES SRL	Italy
E																		Sensors, systems	BTSR INTERNATIONAL SPA	Italy
		x			x														BTTG® / BTTG -Testing Certification	United Kingdom
E		x						x											CAMPEN Machinery A/S	Denmark
	x	x		x	x														CENTEXBEL	Belgium
	x																		Centre Européen des Textiles Innovants	France
	x	x			x													Paper, board, MFC	CENTRE TECHNIQUE DU PAPIER (CTP) (Centre Technique du Papier - The Pulp and Paper Research & Technical Centre)	France
E	x											x						Fine fibers NW, filtration, polymers for medical, recycling of CF	DITF Deutsche Institute für Textil- und Faserforschung Denkendorf	Germany
		x		x	x													Cosmetics, agro, interlinings	EUROFINS ATS	France
		x			x													Cosmetics, personal, hygiene	EUROFINS CONSUMER PRODUCT TESTING GMBH HAMBURG	Germany
T			x															Treating NW hydro-, oleophobic, nanocoatings	Europlasma NV	Belgium
T						ISCC Plus, Oeko-Tex, ISO 9001, ISO 14001 and ISO 50001, BRCGS, EcoVadis, HALAL				x	x							Manufacturer	Fibertex Personal Care A/S	Denmark
T						ISO 9001, ISO 14001 and ISO 50001, BRCGS, EcoVadis, HALAL												Printing, Prototyping	https://innowoprint.com/	Germany
T	x	x	x				x	x										Fiber manuf., the global leader in developing, manufacturing and marketing polyolefin staple fibers for nonwoven applications	FiberVisions	USA
T																		Supplier contacts	Fi-Tech, Inc.	USA
									x		x		x	x	x				Freudenberg Performance Materials (FPM)	
T						ISO-9001, ISO-9002, ISO-14001, Ford Q1, TS 16949									x			Manufacturer	GDC	USA
T		x	x																Fiber-X Finland Oy	Finland
		x			x													Hygiene, sanitary	GALAB LABORATORIES GMBH	Germany
E																		Felting and structuring needles, tools, accessories	Groz-Beckert (Lainto Engineering in Finland)	Germany
E		x	x							x	x								Hills, Inc.	USA
T		x	x			ISO 9001, SHARP, FSC, OSHA VPP, ISO 14001, ISO 50001, ISO 45001, ISO 45003, AS9001D, IATF 16949	x	x	x	x	x	x	x	x	x	x	x		Hollingsworth & Vose	USA
		x																	HY-TEC - HYGIENE TECHNOLOGIE GmbH	Germany
		x			x														IFTH - INSTITUT FRANCAIS DU TEXTILE ET DE L'HABILLEMENT	France
		x		x	x													Paper and textile	INNOVHUB STAZIONI SPERIMENTALI PER L'INDUSTRIA	Italy
	x																		ITA GROUP	Germany
T																		Manuf of diapers and wipes	Kimberly-Clark Corp	USA
T	x					ISO 9001, ISO 14001, ISO 50001, ISO 45001												Styrenic block copolymers (SBC), pine chemicals	Kraton Polymers	Netherlands
		x			x														LUKASIEWICZ RESEARCH NETWORK - TEXTILE RESEARCH INSTITUTE	Poland
E																		Process monitoring	Mahlo GmbH + Co. KG	Germany
E																		Nonwoven winding, stacking, accumulating, cutting, packing	Matthys nv	Belgium
T										x	x							Biopolymer PLA	NatureWorks	
E		x			x		x	x	x	x	x	x	x	x	x	x			NONWOVENS INNOVATION & RESEARCH INSTITUTE (NIRI)	United Kingdom
T						Oeko-Tex 100, FSC													Norafin Industries	Germany
T		x	x							x	x					x	x	Manufacturer of nonwovens	PFNonwovens	Czech Rep.
E		x	x							x	x								Reifenhauser Reicofil	Germany
E																		Components, card clothing	Rieter	Switzerland
	x	x		x							x								RISE RESEARCH INSTITUTES OF SWEDEN AB	Sweden
E		x																	SDL Atlas / Cromocol Sweden	Sweden
		x																	SGS FRANCE	France
		x																	SGS INSTITUT FRESENIUS GMBH	Germany
		x		x	x														Shirley® (subsidiary of BTTG)	United Kingdom
		x				x													STFI - SÄCHSISCHES TEXTILFORSCHUNGSINSTITUT e.V.	Germany
T		x																Polymer provider	Sukano Polymers	Switzerland
	x	x	x				x								x				TAMPERE UNIVERSITY OF APPLIED SCIENCES LTD	Finland
T		x	x															Additives for nonwovens	Techmer PM	USA
E	x						x							x	x				DILO Inc.	Germany
E	x		x				x	x											The DiloGroup	Germany
E	x		x				x	x							x				The DiloGroup / DILO Machines GmbH	Germany
	x	x	x							x	x			x	x	x			The Nonwovens Institute	USA
E		x																	Thwing-Albert Instrument Company	US
		x		x		x													TUV AUSTRIA BELGIUM NV/SA	Belgium
		x				x													TÜV RHEINLAND LGA PRODUCTS GMBH	Germany
	x	x		x															UNIVERSITY OF LEEDS	United Kingdom
	x	x	x		x								x						VTT Technical Research Centre of Finland	Finland
E	x	x	x				x						x	x		x			Trützschler Nonwovens & Man-Made Fibers, Egelsbach	Germany
			x					x											The loop factory	Sweden

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4.2 Digital Platforms in Sustainability Transition – Great Business Opportunities

Katri Salminen & ***Pia Hautamäki***

In this chapter, we introduce digital platforms that could enable sustainability in the nonwovens industry, and to develop its business opportunities. As the nonwovens industry and the machinery used within the industry are already highly digitalised, there is a huge potential of using digital platforms to create sustainable business via the use of data. You will learn about Multi-Sided Platforms, Industry 4.0, Digital Twins, and tools required to build a twin so that both sustainability and business goals can be achieved.

Digital platforms frequently evoke images of web stores or other online businesses offering purchasing opportunities. Yet, in the business-to-consumer (B2C) realm, these platforms are often transactional, facilitating the purchase of products (such as Amazon, Uber, Airbnb, etc.). While there's a wealth of academic studies focusing on the B2C context, research on the business-to-business (B2B) aspect is comparatively sparse. B2B supply chains, along with the products and services provided to B2B customers, tend to be more intricate than those in B2C contexts. Nevertheless, the value generated in B2B interactions is typically confined to the involved parties. However, digital platforms have evolved to represent a novel form of supply chain relationship, designed to deliver value. These platforms facilitate streamlined interactions and transactions between businesses, enhancing efficiency, reducing costs, and offering new opportunities for collaboration and innovation within B2B environments (Anderson et al., 2022; Heikinheimo et al., 2024).

Multi-Sided Platforms Enabling Matchmaking

Digital platforms in the business-to-business (B2B) sector are increasingly recognised for their innovative approaches to value creation, attracting significant attention. Multi-Sided Platforms (MSPs) leverage both tangible and intangible assets to facilitate value by connecting users and enabling more transparent transactions. MSPs operate within a distinct and often complex business landscape, presenting unique challenges for platform operators (Heikinheimo et al., 2024.). To summarise, digital platforms have been defined as 'matchmakers''" that enable productive interactions (Evans & Schmalansee, 2016).

Traditionally, value chains have concentrated on overseeing a linear sequence of vertically integrated activities throughout the customer's purchasing process. This approach undergoes a significant transformation within the platform environment (Hahn, 2020). Within the framework of platform dynamics, key challenges emerge in coordinating value creation for varied user groups and managing the platforms' evolving role in generating value (Hahn, 2020; Ritala & Jovanovic, 2024).

Industry 4.0: Digital Platforms Enable Sustainable Manufacturing

Industry 4.0 (I4.0) refers to the growing trend of automation and data exchange within or between manufacturing processes. At the core of I4.0 are digital platforms which are used to collect, analyse and even visualise data collected simultaneously from devices in a factory or even throughout the supply chain. I4.0 can make the manufacturing of nonwovens more a) efficient, b) sustainable, and c) profitable.

At the core of I4.0 are digital platforms which are used to collect, analyse and even visualise data collected simultaneously from devices in a factory or even throughout the supply chain.

The nonwovens industry is driven by the I4.0 adaptation, namely for more efficient resources and processes, better asset utilisation, service models and aftersales practices, costs of labour, and, finally, quality (see Cloppenburg et al., 2017). In short, this means that the nonwovens industry could benefit from the use of I4.0 technologies such as predictive maintenance and smart machines to reduce costs related to personnel, energy and material waste, machinery, and ineffective supply chains. For the nonwovens industry, I4.0 is a leap towards using digitalisation to promote sustainability in manufacturing (Cubiss, 2022).

A.Celli (2024) has launched tailored I4.0 solutions for the manufacturing of nonwovens and tissue including, but not limited to, machine monitoring, condition monitoring, energy monitoring, and anomaly detection (A.Celli 2024). The solutions enable optimising overall equipment effectiveness which will, for example, reduce manufacturing costs. In practice, this means that I4.0 platforms and services can be used to control the manufacturing cost structure in real time, making it possible for the company to make immediate corrective actions in the case of problems (e.g., machinery downtime or anomalies) in the production process.

Industry 4.0 and Beyond: Digital Twins Can Revolutionise the Manufacturing of Nonwovens

A Digital Twin is an accurate, digital model of a physical factory. It can provide historical and real-time information about monitoring assets and processes, but it can also be used to optimise production, testing, and simulations for the future. Digital Twins are based on I4.0 technologies such as artificial intelligence and connected machines. The clear benefit of a high-maturity Digital Twin is that instead of acquiring information from a single machine, it can capture information from all the machines connected to the system.

Benefits of Digital Twins for sustainability (World Economic Forum 2023; Kamble et al., 2022; Franciosi et al., 2022)

- Resource sharing in the supply chain
- Optimisation of the production process
- Monitoring energy consumption and material waste
- Equipment reliability and predictive maintenance
- Full control of the factory in a single platform
- Downtime reduction
- Better product quality (both when monitoring single-product manufacturing and the quality process in general)
- Carbon footprint calculations
- Optimisation of material use

What is your way of benefiting from Digital Platforms and Twins?

Advantages for the Nonwovens Industry Through and Beyond Digital Platforms

As previous research has demonstrated, digital platforms can enable new economic and technological frameworks that organise transactions and interactions, steering industries towards enhanced sustainable value creation. However, this places a responsibility on the platform orchestrator to serve as a resource-centric matchmaker, focusing productive interactions on efficient transactions in the exchange of excess resources, such as materials in the nonwovens sector (Blackburn et al., 2023).

As a platform orchestrator, a nonwovens company can facilitate the pursuit of sustainable value creation within its operational value network, initiating discussions on how the network can collectively leverage network effects for sustainable value creation. Ideally, as a digital platform scales its activities, it simultaneously enhances productivity in sustainable value creation.

Further, the solutions enabled by I4.0 and digital twin technologies can help the companies to create products with lower environmental footprint and higher quality. Digital Twin technologies are practical in product development as well – the ability to simulate the characteristics of a product, including its potential negative effects on environment, can create a competitive edge for a company operating in the nonwovens business (e.g., Argolini et al., 2023).

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4.3

Engagement of Actors – A Way to Boost New Business

Sven Rassl

This chapter presents insights from the SUSTAFIT collaborative online workshops, attended by professionals in the nonwovens industry (SUSTAFIT, 2024). The workshops focused on engaging different actors within the industry to enhance sustainability. Through a series of sessions, participants explored various aspects of sustainability, including customer-focused strategies, future scenarios, and value networks. The discussions examined different aspects of engaging these actors, highlighting their roles and contributions toward achieving sustainable practices in the nonwovens sector.

Critical Aspects Driving the Shift Towards Sustainable Practices

The discussions emphasised several critical aspects essential for driving the shift towards sustainable practices in the nonwovens industry:

Sustainable Shift in the Nonwovens Sector

Emphasis was placed on the overall need for the nonwovens industry to transition towards sustainable practices, integrating environmental responsibility into every stage of production and consumption.

Manufacturers at the Forefront: Leading Nonwovens into a Sustainable Era

Manufacturers were identified as key players in leading the industry towards sustainability. Their proactive role in adopting eco-friendly practices and innovations is crucial for the sector's sustainable transformation.

Academia's Role in Eco-Friendly Innovations

Academic institutions play a vital role in researching and developing new sustainable technologies and materials. Their contributions are vital for advancing eco-friendly innovations within the nonwovens sector.

Regulations as Catalysts

Regulatory bodies are seen as catalysts for change, providing the necessary framework and incentives to promote sustainable practices. Effective regulations are essential for ensuring industry-wide adherence to environmental standards.

Consumer Demand Transforming Industry

Rising consumer demand for eco-friendly products has compelled producers to prioritise sustainability in nonwovens, resulting in the adoption of greener materials and increased cross-sector collaboration.

The collective insights from the workshops emphasise the necessity for a unified approach to transforming the nonwovens industry. They highlight the importance of cross-sector collaboration, regulatory support, and consumer engagement in achieving long-term sustainability goals.

Eco-Innovation: The Nonwovens Sector's Sustainable Shift

The nonwovens industry is experiencing a major shift towards being more sustainable. This change is not only happening because consumers today care more about the environment, but also because other important stakeholders working with nonwovens want to make products more eco-friendly. Nonwovens manufacturers, universities doing research, regulatory bodies, and consumers advocate for environmentally friendly nonwoven products. By working together and coming up with innovative ideas, these stakeholders are leading the way in making nonwovens more sustainable. Their goal is to make environmental responsibility a core part of how these fabrics are made and used.

Manufacturers at the Forefront: Leading Nonwovens into a Sustainable Era

Manufacturers play a key role in the transition towards sustainability, investing heavily in research and development to create materials and processes that decrease environmental impact. The move towards bio-based and recycled materials proves this trend.

Manufacturers are pioneering the adoption of eco-friendly raw materials like recycled fibres and biopolymers when manufacturing nonwoven textiles.

These innovations are not just about maintaining performance, they also ensure the final products break down in an environmentally accountable way. This approach signals a shift towards sustainability in the industry, displaying manufacturers' dedication to reducing their environmental footprint. By integrating these sustainable materials, manufacturers are leading the change in creating nonwovens that provide the desired functionality while also being designed to decompose or be repurposed at the end of their life cycle. This dual emphasis on performance and environmental impact indicates a major development in nonwoven material production. These efforts are supported by advances in production technologies that aim to lower energy use and waste, indicating a commitment to eco-efficiency and circular economy principles.

Scholars and Sustainability: Academia's Role in Eco-Friendly Nonwoven Innovations

Academics are researching how to improve nonwovens' sustainability. Researchers are looking into plant fibres and new polymers that can reduce environmental impacts and develop materials that improve biodegradability. Studies of nonwoven life cycles provide important data about environmental footprints, enabling improvements to be made. Collaborative initiatives between academic institutions and manufacturers are increasingly common, particularly in Finland, driving forward innovations that merge practical applications with a commitment to environmental responsibility. By working together, universities and manufacturers can leverage their joint ability and resources to address environmental challenges by creating effective and environmentally friendly technologies and processes.

Regulations as Catalysts

Regulatory bodies are critical in shaping the sustainability landscape for the nonwovens industry by introducing laws and guidelines that encourage eco-friendly ways of production. Regulators lay down the environmental benchmarks and compliance rules that motivate innovation and get companies to take on greener technologies and materials.

> *By introducing and enforcing environmentally friendly standards, regulatory bodies make sure manufacturers shift towards practices that lessen environmental impacts, boost resource efficiency, and develop products that perform well without harming the planet.*

These regulations are crucial for steering the manufacturers of nonwoven materials towards a more sustainable future where protecting the earth and industry growth pair up. The policies not only call for sustainable materials but also urge for recycling and accountable disposal, creating regulatory guidelines that support the industry's green transition.

Consumer Demand Transforms the Industry

Consumers interest in environmentally friendly products has grown considerably in recent years, forcing producers to make sustainability a priority for nonwovens. This shift from small niche markets to mainstream buying behaviour means companies need to carefully consider their environmental impact. Groups educating people about environmental problems and pushing for sustainable business practices have driven this change, using social media and partnerships to introduce sustainability into public conversations.

As environmental awareness rises, manufacturers have a need for more sustainable manufacturing processes and materials.

Because of this, companies are now introducing more eco-friendly materials and emphasising sustainability in their marketing. Consumer demand for environmentally friendly solutions is reshaping markets and making sustainability a key factor for innovation and success.

Cooperation is a key to change the nonwovens business for good!

Cooperation and engagement across sectors and different stakeholders are essential for fostering sustainability in nonwovens. Collaborating is a key factor for developing sustainable innovations, overcoming regulatory barriers, and meeting consumer demands for sustainability. Manufacturers are rethinking both materials and processes used for nonwovens, researchers are providing insights and innovative ideas to guide these attempts, and regulators are creating frameworks to encourage sustainable growth. Consumers are vital for driving demand for sustainable offerings, completing the circle of influence, and pushing the nonwovens industry towards sustainability.

Conclusion

The SUSTAFIT collaborative online workshops highlighted the importance of collective efforts among various stakeholders in the nonwovens industry to drive sustainable practices. In conclusion, we recommend that manufacturers, academics, regulatory bodies, and consumers join forces to innovate and adopt eco-friendly methods to achieve meaningful progress. The development of supportive regulatory frameworks and the increasing consumer demand for sustainable products serve as catalysts in this process.

The nonwovens industry is on a progressive route, driven by collaborative initiatives, and a unified commitment to environmental stewardship. This joint effort is essential for overcoming existing challenges and ensuring a more sustainable and digitally integrated future for the nonwovens sector.

The workshops underline the necessity of coordinated innovation and execution. A commitment to sustainability must be shared across various actors, among manufacturers, scholars, regulatory authorities, and consumers. to be effective. The synergy between regulatory support and consumer demand is crucial in advancing sustainable solutions.

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4.4 Value Through Ideation

Pegah Shamloo*, *Pia Johansson* & *Pirjo Kääriäinen

Nonwovens are highly technical products, often hidden from the users' eyes. They're commonly seen as white, single-use items in healthcare or hygiene, with production technologies that are both established and cost-efficient. What role can design and designers play in shaping the future of sustainable nonwovens? In this chapter we show how by embracing design thinking and material-driven design, designers have the power to revolutionise nonwoven materials and processes, guiding them towards a more environmentally friendly direction.

The Multifaceted Role of Design and Designers

Design is far more than just aesthetics – it's a multidimensional discipline that takes a holistic look at products, services, or systems (Brown & Katz, 2019). Design is the behind-the-scenes element in everything we interact with – from the smartphone in our hands to the chair we sit on. Design is about problem-solving and creating seamless experiences for people. From user perspectives and usability to ideation and prototyping, from material and product development to system-level approaches, design encompasses a wide array of considerations.

Understanding user perspectives is central to design. By empathising with end-users and researching their behaviours and preferences, designers gain insights that help shape products and systems that resonate on a personal level. (Brown & Katz, 2019; Norman 2013). This approach ensures that the result is meaningful and user-friendly.

A TIP FOR DESIGNERS:

In nonwoven products, designers might consider factors such as comfort, absorbency, and skin-friendliness. Whether it's designing nappies/diapers for babies or sanitary pads for women, the focus is on ensuring that the nonwoven materials feel soft, provide effective moisture management, and are gentle on the skin. Ease of use and tear resistance are crucial, particularly in applications like medical dressings or industrial wipes, where durability and usability are important.

Bringing value through ideation and prototyping is a key aspect of the design process (Design Council, n.d.). Designers explore a range of ideas and concepts, seeking innovative solutions to complex problems. Prototyping allows for the testing and refinement of these ideas, ensuring that the final designs meet the needs of users and stakeholders. Material and product development are the tangible outcomes of the design process. Selecting appropriate materials and manufacturing processes is essential for achieving the desired functionality, durability, and aesthetic qualities. Collaboration with engineers and manufacturers is often a crucial step in bringing design ideas to life effectively and sustainably.

Taking a system-level approach is also an important aspect of design. This involves understanding the broader context in which a design operates. By analysing how different components interact within a larger ecosystem, designers can create cohesive and sustainable solutions. This involves undertaking a thorough analysis, considering not only the technical aspects but also the environmental, social, and economic factors that influence their use. Designers carefully evaluate how materials interact within the larger ecosystem, identifying both challenges and opportunities for improvement.

Designers in the Material Development Process

Material development processes are long, typically 5–15 years. The journey from the first idea to a commercialised product is seldom linear, and sometimes the results differ completely from the original idea. Technical development is often managed by the EU framework of Technology Readiness Level (TRL) where ideation and experimentation happen in the levels 0–3, and the development process proceeds through prototyping and validation (levels 4–5) towards scale-up and production (levels 6–8) and full commercial application (level 9) (European Commission, 2020). In addition to technical development, human aspects such as usability, consumer acceptance, and life cycle management must be considered in an early stage. In these complex and time-consuming processes, an interdisciplinary team is a must, and designers can bring their skills and methods to support the development in various stages.

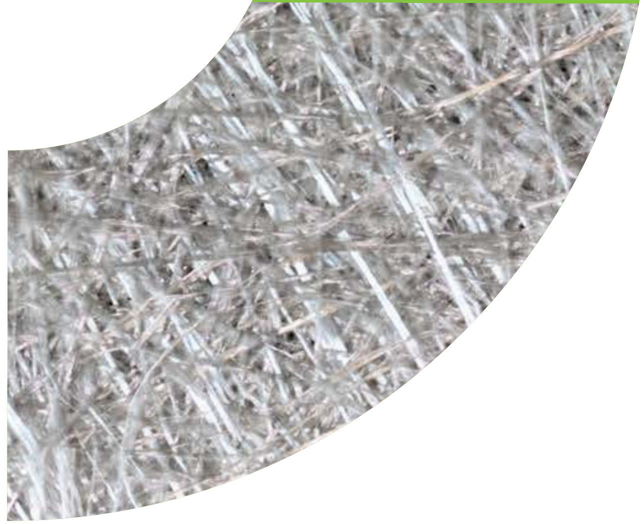
Design professionals, specifically trained in ideation, experimentation, and prototyping, bring valuable perspectives to the material development stage. Questions about potential applications, user profiles, and their expectations guide designers in shaping future products.

A TASK FOR DESIGNERS:

In the ideation stage of material development, designers can support the team's out-of-the-box thinking; a playful or even a futuristic approach broadens the perspective beyond existing technologies and needs.

To avoid causing new problems for our planet, all possible implications of these new ideas and technologies need to be considered already in the early development stage, and designers can help by taking a holistic and critical look at the idea from the human and non-human perspectives by building future scenarios.

As material development progresses into technology validation and scaling-up, the importance of prototyping becomes evident. Designers with specific skills such as textile design, industrial design, or digital 3D modelling can create prototypes and demo products to understand how the material behaves, and to test the material with the future users. Material samples and prototypes are also valuable tools for communication. Visual and textual storytelling is needed to make the technology understandable for stakeholders outside the tech bubble, such as company management, investors, or legislators. However, in the current world of fake stories and misinformation, we need to be careful what we tell – and what we believe. (Kataja, Kääriäinen, 2018).



Understanding the Potential of the Material Through Experimentation

Nonwovens are already so many things, but can they be more? Can they be e-textiles? Can they be treated as solid material? Can they be treated like a sheet of paper? Can they be layered with different fabrics and insulating materials? Can they be solid? Can they be moulded? What polymers can sustainable nonwovens replace? The Aalto University design team working in the SUSTAFIT research project has been constantly experimenting with the material in an iterative process, pushing its borders, exploring new aesthetics and functions and applications.

NEW POSSIBILITIES FOR NONWOVENS:

By experimenting with different fibres, bonding techniques, and surface treatments, designers uncover new possibilities for sustainable nonwovens.

At the heart of the exploration lies the principle of Material Driven Design (MDD), a methodological approach that emphasises the symbiotic relationship between materiality and experientiality. Through MDD, materials are engaged with, not as passive entities to be moulded at will, but as active participants in the design process, each with its unique characteristics, potentials, and stories to tell. This approach calls for a series of iterative, hands-on experiments where designers, material scientists, and end-users become co-creators, each bringing their perspective to the table, each learning from the material as much as it is learned from. (Karana, Barati, Rognoli & Zeeuw van der Laan, 2015). Understanding the potential of nonwoven fabrics begins with a thorough technical and experiential characterisation. This dual-lens approach ensures that the material's physical properties such as its strength, elasticity, and biodegradability are appreciated, along with its ability to evoke sensory experiences, convey meanings, and inspire emotional connections. Through testing and playful exploration, the material's inherent qualities, constraints, and possibilities are uncovered, allowing new application domains where these materials can shine to be envisioned.

Experimental design, in this context, becomes a tool for storytelling, where each prototype, each sample, and each failed experiment adds to the understanding of the material's narrative. It represents a process of discovery which doesn't just reveal how the material behaves under various conditions but also illustrates its interactions with human touch, aging, decomposition, and its eventual return to the earth. This journey of experimentation follows a cyclical, non-linear path, mirroring the life cycle of the materials explored – originating from the earth and ultimately returning to nourish the soil.

The potential of new nonwoven fabrics, therefore, cannot be measured in mere technical specifications or environmental benefits alone. It lies in its capacity to inspire innovative design solutions that are not only sustainable but also meaningful, resonant, and deeply connected to the cycles of nature. Through experimental design, we not only understand the material's potential but also reimagine our role as designers and creators in a world that urgently needs sustainable, thoughtful, and compassionate approaches to materiality. (Valtonen & Nikkanen, 2022).

The Tactile Experience of Sustainable Nonwoven Fabrics

Sensory considerations play a crucial role in the development of new materials. Nonwoven fabrics are particularly important in hygiene products. These products often come into direct contact with our skin, making the tactile experience extremely important. From clothing to hand wipes, surface wipes, and pads, nonwoven materials are constantly interacted with by hand. Moreover, their significance extends further when considering products like disposable face masks, where users breathe through the fabric.

What kinds of product features do customers appreciate?

Given these intimate interactions, it becomes crucial for designers to prioritise the tactile qualities of sustainable nonwoven fabrics. Designers must ensure that these fabrics evoke feelings of cleanliness, safety, hygiene, softness, and purity. By focusing on these aspects, designers can elevate the user experience and promote confidence in the functionality and comfort of sustainable nonwoven products.

In the ethos of Material Driven Design (MDD), the tactile qualities of sustainable nonwovens are not merely by-products of their composition, but deliberate choices aimed at enriching user experiences. This approach involves a meticulous selection of fibres, bonding techniques, and surface treatments that not only meet environmental standards but also cater to the nuanced demands of touch. Through iterative experimentation and user-centred evaluations, designers uncover the tactile vocabulary of these materials – softness, resilience, warmth, and more – that speak to our innate need for comfort and security.(Norman, 2013).

The tactile exploration of sustainable nonwovens also extends to their aesthetic and functional performance. The surface texture, thickness, and flexibility of the fabric must align with its intended use, ensuring that the material not only feels good but also performs optimally.

The tactile experience of sustainable nonwoven fabrics embodies a critical intersection of functionality, comfort, and environmental stewardship. Through the lens of MDD, designers are equipped to craft materials that not only meet the tactile expectations of users but also contribute to a more sustainable world. As we navigate the tactile landscapes of these materials, we are reminded of the power of touch to connect, comfort, and inspire towards a more sustainable future.

Transforming Consumer Behaviours: Rethinking Clean and Sustainability in Nonwovens

In our work, we have had a chance to pioneer a transformative approach in the nonwovens industry, highlighting the need to redefine consumer behaviours towards sustainability, especially for single-use items like nappies/diapers, face masks, and wipes. This redefinition is twofold: altering perceptions of ‘clean’ and ‘cleanliness’ to include environmental impact, and habits that favour biodegradable options over traditional disposal methods.

Redefining ‘clean’ extends beyond a product’s immediate use to its entire life cycle, encouraging consumers to consider not just the effectiveness of a product in maintaining hygiene but also its environmental footprint. Designers play a crucial role in this paradigm shift by developing innovative product designs and materials aligned with sustainability goals. This shift in perception necessitates the creation of innovative product designs and materials that promote sustainability, guiding consumers towards products that are both effective and environmentally responsible. By emphasising the importance of sustainable raw materials and production processes, designers align with growing consumer demands for products that minimise environmental harm, fostering a broader understanding of ‘cleanliness’ that encompasses ecological well-being.

As the nonwovens industry moves towards easily recyclable alternatives, what is your role on the journey?

Integrating circular economy principles into nonwoven products challenges and changes traditional waste management practices. By designing products with end-of-life considerations in mind, such as using easily recyclable or biodegradable materials, designers can contribute to creating more sustainable solutions. This approach advocates for the disposal of biodegradable nonwovens (such as wipes and nappies/diapers) in bio waste rather than general waste, promoting industrial composting and recycling as viable end-of-life options. Such initiatives not only align with the environmental consciousness of consumers but also offer practical solutions to waste management challenges traditionally associated with these products. (Ellen MacArthur Foundation, 2017).

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5.

FUTURE OUTLOOKS

In the final section of the workbook, we position ourselves to look towards the future of sustainable nonwovens and explore potential collaborations between industry, universities, and research institutions.

5.1 Future Research Endeavours

Pia Hautamäki, Ali Tehrani** & **Antti Oksanen

In this chapter we cast our thoughts into the future and lead you to think about the activities that need to take place to pave the way for sustainable nonwovens in the future. The SUSTAFIT research project, conducted from September 2022 to 2024, focused on studying fit-for-purpose nonwovens. Our goal was to develop segment-specific sustainable nonwoven materials using eco-friendly fibres and chemicals, while also creating environmentally friendly variants with enhanced performance through the exclusive use of natural agents for hydrophobising and antimicrobial purposes. We developed an understanding of various perspectives by studying sustainable nonwovens. Based on our work in the research project and the studies we reviewed, this chapter focuses on illustrating future research areas within the nonwovens sector.

Sustainable Alternatives to Nonwovens

The exploration of sustainable alternatives to traditional nonwoven products is a critical research avenue.

As evidenced by the market's positive response to reusable products like cotton pads, menstrual cups, and beeswax wraps, there is significant potential for more environmentally friendly products that could replace or complement existing nonwovens (EDANA, 2023b).

Identifying materials that are both sustainable and capable of meeting the diverse requirements of nonwoven applications remains a promising yet challenging research goal. This effort aligns with the need to expand on exploring both the materials and the technological innovations that can enhance product life cycle sustainability. Thermoplastics like polypropylene are widely employed in single-use nonwovens manufacturing, yet substituting these with biodegradable alternatives like Polyhydroxyalkanoates (PHA) represents a significant advancement. Although current PHA production levels fall short of market demands, the landscape is set to rapidly evolve in the near future, promising a transformative shift toward more sustainable material choices.

Forests are, additionally, a valuable natural resource in Finland, providing an abundant source of wood-based cellulose fibres essential for nonwoven production. Cellulose is not thermoplastic and therefore meltblowing, the most common nonwoven production method, cannot be adopted for the production of cellulosic nonwovens. Common alternative methods for converting short wood-based fibres into nonwovens include airlaying, wetlaying, and foamlaying, while carding and needle punching are suitable for longer fibres. Each method presents distinct advantages and shortcomings when it comes to water and energy consumption. Future studies should delve deeper into these aspects, conducting thorough techno-economic analyses to provide a comprehensive understanding.

The majority of fossil-based synthetic nonwovens find application in single-use products such as nappies/diapers, medical textiles, and face masks. These materials typically exhibit hydrophobic and antibacterial properties. To incorporate similar functionalities into cellulosic nonwovens, eco-friendly methods are needed. Through the exclusive use of bio-based, biodegradable chemicals, we have successfully developed hydrophobic and antimicrobial cellulose nonwovens in SUSTAFIT, thereby enhancing the market position of cellulose-based nonwovens.

To advance the development of fully bio-based and biodegradable medical textiles, filters, and face masks, it is essential to prioritise further studies focusing on testing various parameters.

Potential parameters for testing include particle and bacterial filtration efficiency, breathability, fluid resistance, splash resistance, flammability, and more. By rigorously assessing these factors, we can ensure the efficacy, safety, and environmental sustainability of these innovative bio-based materials, facilitating their successful integration into healthcare settings and beyond.

Further, there exist sustainable fibres for nonwoven manufacture such as PLA (polylactic acid). However, in many cases they are too expensive, and their availability is limited. Sustainable techniques to produce cellulosic fibres (for example IONCEL and BIOCELSOL spinning processes) with high performance and reasonable cost are developing fast, promising new products to markets in the future. Alternative nonwoven manufacture technologies such as foam forming may enable the use of otherwise inapplicable raw materials such as recycled textiles. Further, combining different nonwoven manufacturing techniques to produce layered structures can be used to achieve high performance, for example, to extended lifetime and durability, but also sustainability with the recyclability and high cellulose fibre content at same time.

Nonwoven materials are pivotal across diverse industries, from healthcare to consumer goods, due to their versatile applications. Despite the growing number of regulations promoting more sustainable materials in the EU, particularly the directives related to single-use products (SUP) that impact nonwovens, the applications of nonwoven materials continue to expand, as reported by EDANA (2023a). In the nonwovens industry, the opportunities for innovation are increasingly geared toward sustainability. This chapter explores these innovation opportunities and revisits the pressing need for research into sustainable alternatives, consumer behaviour, recycling technologies, and industry compliance with evolving standards.

Consumer Awareness, Disposal Practices and the Market

A gap remains in consumer awareness regarding the proper disposal of nonwoven products (EDANA, 2023b). This situation suggests a need for focused research on the effectiveness of educational programs and labelling, such as the 'Do Not Flush' symbol for feminine hygiene products, to promote proper disposal practices.

More information, marketing, and communications are needed for consumers to change consumer behaviour.

Additionally, there is a noted reluctance to adopt reusable alternatives for products such as nappies/diapers and menstrual products, necessitating further research into making these products more appealing and practical for everyday use (EDANA, 2023b). These findings could lead to broader research themes around consumer behaviour, examining how the dissemination of information affects recycling and reuse rates in the context of nonwoven products.

What About These Possibilities?

Furthermore, these findings could lead to activities aimed at increasing marketing awareness throughout the entire B2B value network of the nonwovens industry. This expansion would also necessitate forays into further research areas, such as investigating how to promote sustainable products initially within the value network and identifying marketing tactics that increase consumer acceptance of sustainable purchases. Additionally, it is essential to investigate pricing strategies for sustainable alternatives. Research should evaluate how pricing influences consumer choice, particularly in contexts where sustainable products are priced higher than their less sustainable counterparts. Understanding consumers' willingness to pay for sustainability across various market segments could lead to more effective marketing and production strategies.

Advancing Recycling Technologies and Sustainability Practices

Research is crucial in the area of recycling technologies for single-use nonwovens, especially those used in hygiene products. According to the Waste to Resource Initiative report, there is a significant gap in effective recycling methods, pointing to an urgent need for innovative solutions that can transform nonwoven waste into a resource (Berninger, Frick & Burgstaller, 2023). Furthermore, nonwovens are extensively used in critical areas such as the medical industry, where their use has surged by 40% from 2019 to 2022 (EDANA, 2023b). This underscores the necessity of single-use nonwovens for maintaining hygiene and safety standards.

Recycling 100% cellulose nonwovens into new nonwovens and textile fibres is feasible, although challenges arise from the presence of binders and impurities, necessitating their removal, which may increase recycling costs. In the SUSTAFIT research project, successful recycling of textile waste into nonwovens using carding and needle punching techniques has yielded promising results.

Within the project, we also managed to convert cellulosic nonwovens into textile fibres successfully through IONCELL technology.

Future research should explore the sustainability of these practices, particularly in industries where disposable products are mandatory. The development of nonwovens that meet both safety and environmental standards could be a significant step forward, requiring a multidisciplinary approach that balances regulatory compliance with environmental sustainability.

Heading into the Future

There are multiple ways to address the waste problem in the nonwovens industry, including reducing overproduction and overconsumption, extending product lifetimes, and designing products for increased circularity. There is room for new innovations, and we still need more research on how to turn textile waste into new fibres that can then be used to create new clothes or other textile products, or material for nonwoven products. Additionally, we need to investigate the traceability within nonwovens, which is still in its early stages due to the multi-layered materials that comprise nonwovens. Some reports indicate that a large amount of textile waste could be recycled fibre-to-fibre, while some may require open-loop recycling or other solutions. However, recycling textiles for use as textiles material that can be used in nonwoven products offers potential for the future.

In summary, future research directions in nonwovens call for a comprehensive approach that addresses technological innovation, consumer behaviour, economic factors, and regulatory compliance. By focusing on these areas, the nonwovens industry can better align with global sustainability goals while continuing to meet the diverse needs of consumers. The insights gained from the SUSTAFIT research project and other research initiatives could help pave the way for a more sustainable future in the production and usage of nonwovens, benefiting both the industry and the environment.

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BIOGRAPHIES OF RESEARCHERS

M.Sc. (Tech.) Olamide Badara, Researcher, Tampere University of Applied Sciences. Olamide worked as a researcher with the SUSTAFIT project, where she developed nonwovens from sustainable fibres. Olamide's focus is on the preparation and characterisation of needle-punched and wet-laid structures from recycled textile-based fibres and man-made cellulosic fibres.

BA (Hons) Design Management Anna Garton is a Post-Consumer Textiles Expert at municipal waste management company Lounais-Suomen Jätehuolto Oy (LSJH) which coordinates the separate collection of end-of-life textiles in Finland. Anna works to find new solutions for recovered and sorted textile as raw material. Anna has brought her practical experience to the SUSTAFIT project to find new nonwoven applications that use recycled content.

M.Sc. (Tech.) Esubalew Kasaw Gebeyehu, Doctoral Researcher in Textile Chemistry group at the Department of Bioproducts and Biosystems, Aalto University. Esubalew has a rich background in teaching and research activities in textiles. Within the SUSTAFIT project, he was working on improving the hydrophobicity and antimicrobial property of cellulosic nonwovens.

M.BA Shruti Dharwadkar has a robust background in sustainable textiles and business-related research. Her expertise lies in blending risk management with circular economy principles. As an entrepreneur, Shruti has focused on developing innovative solutions within the sustainable textiles sector to promote environmental sustainability and strengthen business resilience.

Dr., Docent Pia Hautamäki, Principal Lecturer and Researcher, Tampere University of Applied Sciences. Pia works at the Tampere University of Applied Sciences' Applied Research Center as Principal Lecturer and Researcher, as well as the Director of the SUSTAFIT research project. Pia's research interest is focused on sales management and sustainability in sales. Her research articles have been published in international scientific journals.

Dr. Pirjo Heikkilä, Principal Scientist and Project Manager, VTT technical Research Centre of Finland Ltd. Pirjo has 25 years of experience in textile and fibre materials research. Her recent research focus areas have included, for example, textile recycling and circular economy topics as well as sustainable nonwoven materials and technologies, and she has applied her knowledge and experiences in SUSTAFIT's sustainability strategy work.

Ph.D., M.Sc. (Tech.) Marita Hiipakka, Senior Officer, Chemical Products, Finnish Safety and Chemicals Agency. Marita has over 20 years of experience in R&D research projects including molecular biology, polymer materials, and circular economy. In the SUSTAFIT project, Marita was mainly responsible for the end-of-life testing of nonwovens.

Dr. Michael Hummel, Associate Professor, Department of Bioproducts and Biosystems, Aalto University. Michael has more than 10 years of experience in cellulose fiber spinning and he is one of the inventors of the Ioncell® process. In the SUSTAFIT project, Michael and his team produced cellulose fibers for nonwovens from alternative feedstocks such as straw pulp and recycled nonwovens, and developed fibers with in situ antimicrobial properties.

BA Pia Johansson, Master's student in Industrial and Collaborative Design, Aalto University. With a background in textile design and bio-based materials, Pia has developed expertise in the intersection of textiles and chemistry. Presently, Pia's work focuses on incorporating interaction design principles into textile interfaces, aiming to enhance user experience and functionality.

Lic. Phil. Piia Kanto, Senior Lecturer, Tampere University of Applied Sciences. Piia is Senior Lecturer in the Laboratory Engineering degree programme. Piia's expertise is in chemistry. Piia has experience of working in various projects related to sustainable materials. In the SUSTAFIT project Piia has mostly worked with consumer study and end-of-life options of nonwovens.

MA Pirjo Kääriäinen, Associate Professor in Design and Materialities, Department of Design, Aalto University. Since 2011, Pirjo has been facilitating interdisciplinary CHEMARTS education and research with a focus on bio-based materials and a design driven approach to material development. Her background is in textile design and in the textile industry.

Dr. Marjo Määttänen, Principal Scientist and Project Manager, VTT technical Research Centre of Finland Ltd. Marjo has over 25 years of experience at chemical pulping and regenerated cellulose fibre development. Her recent research has focused on the development of processes for making sustainable regenerated cellulose textile fibres including pre-treatment of different cellulosic feedstocks and the development of cellulose carbamate and Biocelsol technology. In the SUSTAFIT project, she focused on the preparation of chitosan containing Biocelsol fibres.

Dr. Antti Oksanen, Senior Scientist and Project Manager, VTT technical Research Centre of Finland Ltd. Antti has worked as project manager in contract consortium projects, as well as in EU and nationally funded projects. He has recently worked in projects related to forest and nonwoven industries where one of the main targets has been the replacement of oil-based and otherwise harmful materials with sustainable alternatives. In the SUSTAFIT project, he coordinated VTT project activities, and led the task 'novel concepts and structures to improve performance'. Besides project management, Antti has long history of piloting unconventional technologies to produce upgraded or new products.

Ph.D., M.Sc. (Tech), B.Sc. Arts Sara Paunonen, Senior Scientist, VTT Technical Research Centre of Finland. Sara has an extensive and international career in research on biobased materials, including binder chemicals, composites, nonwovens and packaging materials, fiber web processes, material physics, cellulose fiber-water interactions, process data analysis, and product design. In the SUSTAFIT project, Sara was the WP leader for the work related to fibers and fiber webs.

D.Sc. (Tech.) Hanna Pihlajarinne, Head of Competence Area in Tampere University of Applied Sciences. Hanna has over 20 years of experience in different roles and responsibilities in industry, mainly in product development and leadership. She has been participating in different RDI projects concerning innovations and their commercial preparations. In addition to current responsibilities at the Tampere University of Applied Sciences, she is also Managing Director and founding partner of spin-off company Aeroff Oy.

M.Sc. (Tech.) Noora Raipale, Research Scientist, VTT Technical Research Centre of Finland. Noora works as a research scientist within textile and nonwoven materials group at VTT Technical Research Centre of Finland, and as a task leader in SUSTAFIT's segment-specific sustainability strategies work. Noora's research focuses on the development of novel fibre-based products together with sustainable solutions with a focus on textiles, nonwovens, and packaging cushioning materials.

B.Sc. Timo Rantanen, Senior Research Technician, VTT Technical Research Centre of Finland. Timo has over 10 years of extensive experience as an operator in the SAMPO and SUORA pilot environments. He is currently the responsible person at site. He also participates in planning and modifying the pilot environments and developing them further to respond to evolving research needs.

M.Sc. (Tech.) Virpi Rämö, Principal Scientist, textile applications, Kemira Oyj. Virpi has over 15 years of experience in R&D and product development focusing on sustainable materials and chemistry. In the SUSTAFIT project, Virpi was one of the project's initiators gathering together the consortium and later acting as a steering group member.

M.Sc. (Tech.) Tonmoy Saha, Research Assistant at Aalto University. Saha is doing his second Master's degree within the Textile Chemistry Group at Aalto University. Saha has some experience of working on textile projects. In the SUSTAFIT project, he was working on imparting antimicrobial properties to cellulosic nonwovens using bio-based agents and convenient post-treatment methods.

Dr. Katri Salminen, Project Manager, School of Industrial Engineering, Tampere University of Applied Sciences. Katri has nearly 20 years of experience in research related to industry, industry digitalisation, and sustainable manufacturing. She has published several papers on Industry 4.0 and digital platforms. In the SUSTAFIT project, her work related to research regarding strategies and attitudes that could make sustainable nonwovens more attractive to the general public.

BA Pegah Shamloo, Master's student in Contemporary Design, Aalto University. Rooted in industrial design, Pegah's design philosophy is anchored in the exploration of novel materials and methods and their potential to transform user experiences. In her Master's thesis she explores new frontiers in sustainable and material-driven design by experimenting with the pioneering nonwoven fabrics developed in the SUSTAFIT project.

M.Sc. Tiinamari Seppänen, Research Scientist, VTT Technical Research Centre of Finland. Tiinamari's research focuses on the development of functional cellulose fiber materials, mainly via foam forming. She has been developing, e.g., functional non-wovens, packaging materials, and bio-composites both at the laboratory and on a pilot scale, and also studied the interfacial interactions in cellulose fiber foams.

Dr. Ali Tarhini, Postdoctoral Researcher at Aalto University. Ali works within the Textile chemistry group in the Department of Bioproducts and Biosystems at Aalto University. He has extensive experience working on different projects related to bio-based material, composites, and cellulosic fibers. In the SUSTAFIT project, he was involved in the functionalisation of cellulosic nonwovens focusing on improving their antimicrobial and hydrophobic properties.

Dr. Ali Tehrani is an Associate Professor in the Department of Bioproducts and Biosystems at Aalto University. With expertise in Textile Chemistry and Fiber Science, Ali currently leads the Textile Chemistry research group at Aalto. In the SUSTAFIT project, he coordinated Aalto project activities and led the Work Package focused on the improved performance of bio-based nonwovens.

M.Sc. (Tech.) Minna Varheenmaa, Lecturer, Tampere University of Applied Sciences. Minna has versatile experience in project management and practical implementation in textile research, testing and development, as well as in standardisation and teaching. She managed the Sustainable and Smart Textiles project in the Tampere region. In SUSTAFIT, Minna has made contributions to the project especially by gathering information on service providers for nonwoven testing and piloting.

Sustainable Nonwovens of the Future – From Research Into Business Opportunities

This practical workbook distills insights from the 2022–2024 SUSTAFIT research project into an easily implementable guide.

This practical workbook explores

- the market opportunities available when aligning business strategies with sustainable practices;
- new business models for single-use nonwovens and segment-specific sustainability strategies;
- technical perspectives on manufacturing nonwovens sustainably, focusing on novel raw materials, innovations, end-of-life options, and scalability through piloting; and
- the importance of building ecosystems by engaging service and test bed providers, leveraging digital platforms, and fostering collective stakeholder efforts to create value.

We hope you find this practical workbook insightful and inspiring, offering valuable information. Enjoy discovering how to make your industry more sustainable and your business more successful for the future!

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