SUSTAFIT – Sustainability Strategies for Nonwovens

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Published: 13/06/2024

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RESEARCH REPORT

VTT-R-00571-23

SUSTAFIT – Sustainability Strategies for Nonwovens

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Confidentiality: VTT Public

Version: 05.06.2024

VTT

beyond the obvious

Report's title	
SUSTAFIT – Sustainability Strategies for Nonwovens	
Customer, contact person, address Business Finland and Project consortium	**Order reference** 561/31/2022
Project name Sustainable fit-for-purpose nonwovens	**Project number/Short name** 133618/SUSTAFIT
Author(s) Noora Raipale, Pirjo Heikkilä	**Pages** 72
Keywords Nonwovens, sustainability strategies, sustainability	**Report identification code** VTT-R-00571-23

Summary

Nonwovens play a vital role in various industries, such as hygiene, geotextiles, automotive, and construction, and in the last decade, there has been a high increase in the production and consumption of nonwovens. Due to complex nature of products and applications, the recycling rates of nonwovens have remained low, and a lot is needed to enable fully circular value chains. Legislation and regulations are pushing towards more sustainable actions inside the EU, especially focusing on single-use products, thus more sustainable approaches have to be found. In many sectors sustainability has become a critical property, however, it has been noticed that there are no clear guidelines to improve sustainability likely due to the varying needs, lifetimes and functionalities associated with nonwovens.

The focus of this report is on clarifying how different types of nonwovens can be made more sustainably from environmental point of view, considering existing sustainability strategies focusing on textiles, requirements in different nonwoven segments and the lifetime of the products. Drivers for more sustainable practices are considered – some regulations and existing sustainability strategies. After background information, the study subsequently dives into a range of sustainability strategies that have been proposed to enhance the sustainability of nonwoven products.

The selected sustainability strategies were tailored to the specific combination of product lifetime, technical requirements, and other needs for each nonwoven segment. Regarding product lifetime, the target on single-use or disposable nonwovens to reduce the environmental impacts is high in material choices. Multi-use and longer-lasting products are required to be durable and withstand repeated or long-lasting use, and here, the focus is more on high durability and repairability to maximize the product's lifespan without losing its functional properties. Regarding technical requirements, if the structure is more complex or more specific performance are needed, more important is to keep desired performance for proposed lifetime, or even lengthening the lifetime if the performance can be preserved longer. It was also found that sustainability must be considered in all parts of the product cycle. Proper lifecycle assessment (LCA) should be made when deciding use of new raw materials or production technologies case-by-case to validate if the new approach is truly more sustainable choice.

Confidentiality	VTT Public

Espoo 05.06.2024

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Distribution (customer and VTT)

VTT, Business Finland, project partners

Approval

VTT TECHNICAL RESEARCH CENTRE OF FINLAND LTD

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Preface

This report is a part of Business Finland -funded SUSTAFIT-project (Sustainable fit-for-purpose nonwovens project), which is a research project established to boost Finnish industries competitiveness and broaden the opportunities in nonwoven markets. The SUSTAFIT project is followed by industrial partners who are influential actors in the Finnish nonwovens value chain.

This report is included in work package 1, “Sustainable Nonwovens”, led by TAMK, and especially included in task T1.1 Segment-wise sustainability strategies led by VTT. The report introduces different nonwoven segments, their requirements, and segment-wise sustainability strategies in order to create more sustainable practices in different nonwoven segments. The report includes case studies to clarify what are the most important sustainability strategies in different product groups as different segments and products have varying needs. The results from this report can be used to understand the needs and areas to focus on while making a shift towards a more sustainable sector.

Authors extend gratitude to the consortium partners for their invaluable contributions during the consortium meetings and workshops organized in the project. The active participation and insightful perspectives have been helping in shaping the sustainability strategy work.

Espoo 12.6.2024

Contents

Abbreviations and terms

AHP	Absorbent Hygiene Product
ASTM	American Society for Testing and Materials
Bico	Bi-component fibre
C2C	Cradle to Cradle, Consumer-to-Consumer
CAC	Carded-airlaid-carded
CEN	Comité Européen de Normalisation, i.e., European Committee for Standardization
CMC	Carboxymethyl Cellulose
EC	European Commission
EDANA	European Disposables and Nonwovens Association
EMS	Environmental Management System
EPA	Efficient Particulate Air Filter
EPR	Extended Producer Responsibility
GHG	Greenhouse Gases
HEPA	High Efficiency Particulate Air Filter
HVAC	Heating, Ventilation, and Air Conditioning
INDA	Association of the Nonwoven Fabrics Industry
IPM	Integrated Pest Management
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
MMCF	Man-Made Cellulosic Fibre
NMMO	N-methyl Morpholine N-oxide
OECD	Organisation for Economic Co-operation and Development
PA	Polyamide
PE	Polyethylene
PES	Polyester
PET	Polyethylene Terephthalate

PLA	Polylactic Acid
PHAs	Polyhydroxyalkanoates
PP	Polypropylene
RH	Relative Humidity
rPET	recycled PET
SAP	Superabsorbent Polymer
SFS	Central Standardization Organization in Finland (Suomen Standardisoimisliitto)
SMS	Spunlaid-meltblown-spunlaid
SUP(D)	Single-Use Plastics Directive
TED	Textiles Environment Design
ULPA	Ultra-Low Penetration Air Filter

1. Introduction

Globally, textile industry contributes to approximately 10% of total pollution, being the second largest industrial source of pollution after aviation. Over the last decades, the textile industry has grown enormously and continues to grow at a fast pace, even though environmental impacts have been widely recognized, and laws and regulations have been implemented to make substantial changes towards more sustainable practices in the textile industry. The sustainability should be considered in all steps of the value chain, from designing to raw materials extraction, production, consumption, and end-of-life, and to create wider understanding of making transition towards more sustainable industry, collaboration of policymakers, manufacturers, stakeholders, and end users is needed.[1]

Inside the textile sector, nonwovens are an important group of textiles, since nonwovens are versatile materials that are used almost everywhere around us – from hygiene and medical products to filtration, agriculture, automotive and geotextiles, both in consumer and industrial products. Nonwovens can be designed and manufactured for certain application with the selection of raw materials, formation, and bonding methods together with finishing treatments, and the end product can be for example lightweight and thin, strong, and durable.[2] Nonwovens are defined by different standards and definitions:

ISO STANDARD 9092 and CEN EN 29092:

A nonwoven is 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.

ASTM D 1117-80:

A nonwoven is a textile structure produced by the bonding or interlocking of fibres, or both, accomplished by mechanical, chemical, thermal, or solvent means and combinations thereof. The term does not include paper or fabrics that are woven, knitted or tufted.

In the last decade, there has been a substantial growth in nonwovens, and however, at the same time, more legislation and regulations have entered into force regarding single-use and fossil-based products, and both, consumers and companies have started to pay more attention to make more environmentally responsible choices.

Even though legislation and regulations are pushing towards more sustainable actions especially inside the EU, and there is a drive for sustainable processes and products, there are no clear guidelines for improving sustainability in different nonwoven product segments. The aim of this report is to collect these needs and sustainability drivers by mapping of different existing nonwoven product segments to gain understanding on the landscape. The focus will be on clarifying how different types of nonwovens can be made more sustainably from environmental point of view, and existing sustainability strategies especially for textiles will be considered, creating segment-wise sustainability strategies for selected types of nonwovens.

The concept of sustainability unites three different dimensions – social, environmental, and economic – which cover different areas that are needed to support wise use of resources. The topic of sustainable development started to gain importance significantly after 1980s, and in 1987, the Brundtland Commission of the United Nations published a report, *Our Common Future*, in which they described the guidance, basic principles for sustainable development, and one of the most cited definitions of sustainable development nowadays[3]:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

For a business or process to meet goals of sustainability, it should benefit **society** – standards of living, education, and give equal opportunities to people, be **economically viable** – ensure growth and profit together with cost savings and development in research and development (R&D) and should not cause irreversible changes to the **environment** – take care of responsible use of natural resources, prevent pollution, and take care of biodiversity.[4]

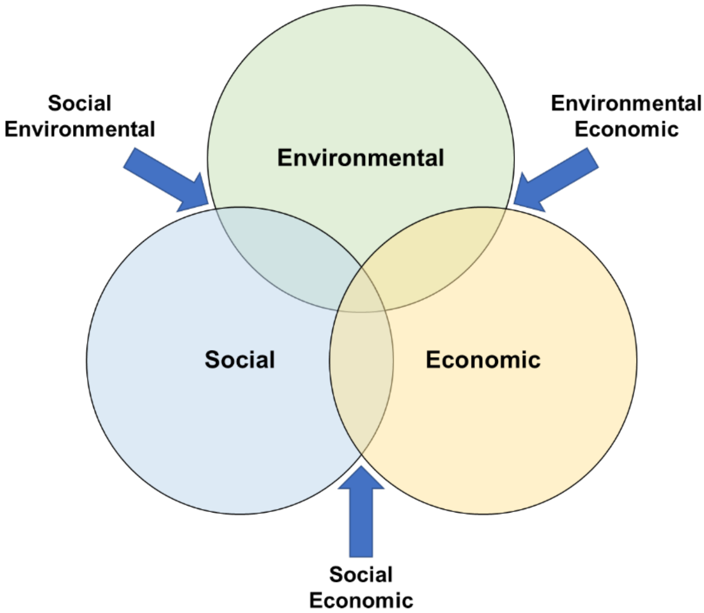


Figure 1. Overlap of the environmental, economic, and social aspects of sustainability.

In this report, the objective is especially on the environmental aspect of sustainability, as in nonwovens sector, many production processes could be more ecological since fossil-based raw materials together with chemicals and high water and energy consumption are common in the production of many nonwovens. In addition, poor recyclability or biodegradability of some nonwovens is a problem to tackle. However, as seen from Figure 1, the aspects of sustainability overlap with each other, so even though the objective in this report is on the environmental aspect of sustainability, all aspects are important to be taken into account when creating more sustainable actions.

This report starts with briefly explaining the manufacturing of nonwovens from web formation to bonding techniques and finishing. Next, the commonly used raw materials for nonwovens are introduced. Then, different nonwoven segments together with their requirements or needs are shown. The different sustainability drivers for nonwovens – regulations and existing sustainability strategies are explained to further use these to create segment-wise sustainability strategies for nonwovens.

In this report, the following methods have been used to create segment-wise sustainability strategies for nonwovens:

1) Extensible literature search to gather background information on nonwovens, their raw materials, production, and applications, and to find relevant sustainability drivers and strategies to be applied to different nonwoven segments
2) Collaborative workshops with industrial partners and companies to get insights for creating sustainability strategies

In the literature search to gather background information for nonwoven manufacturing and raw materials, the main references used were *Handbook of Nonwovens* from Russel, S.J. (2007), and *Nonwovens – Process, Structure, Properties and Applications* from Karthik et al.[2,5] These references were mainly used for the nonwoven segments and requirements sections as well, but the requirements for different nonwovens are found from *Edana* website[6]. In addition, various research articles, reports and previous project results were used as references especially for creating segment-wise sustainability strategies to gather what kind of changes could be made in order to achieve more sustainable sector.

2. Manufacturing of nonwovens

2.1 Raw materials in nonwovens

Nonwovens are composed of fibres as the main raw material like other textile materials, but their manufacturing process is simpler as it does not contain manufacturing of yarns and weaving. Nonwovens can be made from fibres or directly from polymers, and in addition, also binders and other additives can be used in the production depending on the desired properties and end-use application.

The raw materials used in nonwovens are commonly classified roughly based on the source of the material – natural fibres and synthetic fibres. The classification can also be done based on the length of the fibre, staple fibres, or filaments, as the length of the fibres also affects the choice of web formation method used. Another way of classification is based on chemical composition – such as cellulosic (natural and regenerated), polyamides, and polyesters.

Synthetic fibres are the most used fibres for nonwoven applications as they are generally affordable, easy to process and result in good web properties. Most common synthetic fibres used are fossil-based, such as polypropylene (PP), and polyester (PES) (Figure 2). Use of natural fibres and materials, for example, cotton and wood pulp, has been lower compared to use of fossil-based raw materials in nonwovens, depending also on the application area, but interest towards the use of bio-based, novel regenerated cellulosic fibres or man-made cellulosic fibres (MMCF), and recycled fibres has risen due to sustainability considerations.

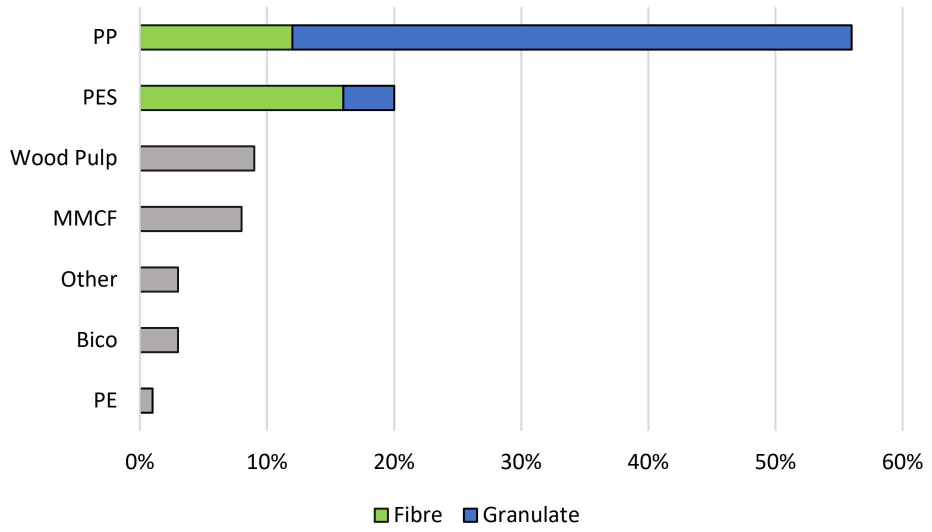


Figure 2. Market share of different raw materials for nonwovens in 2022 ('000 tonnes) PP = Polypropylene, PES = Polyester, MMCF = Man-made cellulosic fibres, Bico = Bi-component fibres, PE = Polyethylene.[7]

The selection of raw materials affects the parameters in the processing phase, such as web weight uniformity, breakage of the web, and web cohesion. These parameters are influenced, for example, by fibre properties such as diameter, length, and tensile strength. The selection of raw materials highly affects the sustainability of nonwovens in the whole value chain as the choice of raw materials affects the manufacturing phase (web formation, bonding, and finishing), consumption and end-of-life, especially the recyclability, and circulation of the used materials. In addition, also cost and processability are a few of the most important parameters that affect the selection of raw materials.

2.1.1 Natural fibres and materials

From natural **plant-based fibres**, cotton is the most common fibre to produce nonwovens. Cotton is known for its excellent absorbency, comfort, and natural haptics; thus, it is utilized especially in hygiene sector including for example hygiene wipes, and female hygiene products. The downside of using cotton is usually the high amounts of water consumption in the cultivation phase, together with the use of significant amounts of pesticides and herbicides, although in production of organic cotton the use of pesticides and herbicides is reduced, and only natural fertilizers are allowed to be used. In addition, cotton is nowadays mostly grown in areas where cotton would not naturally grow, which increases the amount of water consumption, and increases the salinity of the soil. Since cotton absorbs more water compared to many synthetic fibres, also in colouring and finishing treatments the water and chemical consumption is high.

From natural materials, also wood pulp is rather cost-effective raw material type which can be produced at high volumes. Most wood pulp include much shorter fibres compared to textile fibres, with length less than 5 mm. Wood pulp is often blended with other longer fibres. Wood pulp is very commonly used in absorbent products, such as wipes, napkins, diapers, and sanitary napkins as an absorbing layer. Other annual corps such as flax, hemp, jute, linen and abaca are also used in nonwovens. Products range from coarse mats made from mechanically processed fibres to premium fabrics where materials have gone through complex opening and purification treatments.

Animal fibres are not that widely used in nonwovens compared to use of other fibres, but wool is the most used animal fibre used in nonwovens. Wool is a natural fibre that is obtained mostly from sheep. In general, it is a strong, resilient, and insulating material that is commonly used in clothing, carpets, and other textiles. Wool can be used as the primary fibre, or it can be blended with other fibres to create fabrics with specific properties. Some of the common applications for wool nonwovens include medical supplies, insulation materials, and protective clothing. Wool is also biodegradable and can break down naturally in the environment. Although, wool may not be suitable in certain applications, such as those that require resistance to chemicals or high temperatures, and also, the production of wool requires large amounts of land and water. Silk is also another naturally occurring animal (protein) fibre which is not that widely used in nonwovens.

Table 1. Strengths and weaknesses of natural fibres in nonwovens.

Strengths	Weaknesses
• Usually high comfort • Hypoallergic (cotton) • High absorbance → advantage in absorbent nonwovens, for example in wipes and diapers • High wet strength (cotton) • Potential for new innovative sustainable products (R&D) • Bio-based, biodegradable, recyclable • Applications of *disposable* products (for example wet wipes) growing → Need of absorbing raw materials • Wood pulp is more affordable compared to many sustainable man-made cellulosic fibres (MMCFs) • Wood pulp is available at relatively low cost and high volumes • Drivers for reduction of fossil-based plastics (e.g., SUP Directive) • E.g., recycled cotton could be used to produce for example nonwoven composites with high thermal and sound insulation properties	• Poor elasticity • Some pill easily (lint can form from short fibre length) • Mechanical properties weaken when recycled • Competition with synthetic fibres that have higher wet strength and other mechanical properties • High water consumption (cotton cultivation, dilution of wood pulp) • High amount of chemicals and pesticides used (cotton cultivation) • Consumer preferences – cheap single-use plastic products, bio-based “not as high quality” (misconceptions) • Contamination from synthetic dyes → challenges in recycling • High cost compared to synthetic fibres and polymers • The prices of the natural fibres might rise when regulations push towards use of natural fibres and demand increases

2.1.2 Man-made fibres

Man-made fibres are the most common raw materials in nonwovens production – over 90% of total output of nonwovens are produced from man-made fibres. Synthetic polymers (e.g., PP, PES, and PA), bio-based polymers (e.g., PLA and PHAs) and regenerated cellulose-based fibres (e.g., viscose, Lyocell) make up the three major classes of man-made fibres. In addition to these, recycled alternatives of different fibre options are nowadays used for making nonwovens.

The most typical **fossil-based or synthetic fibres** used in nonwovens are PP, PES, and PA. Fossil-based fibres are widely used in different nonwovens due to high mechanical properties together with generally affordable price. The nonwovens made from these fossil-based raw materials can be produced from polymers via direct methods (meltblowing or spunbond), and continuous filaments can be formed, or also via dry or wet methods from fibres which are cut to desired length.

These synthetic fibres have many beneficial characteristics for nonwovens, such as generally affordable, strong, durable, thermoformable, lightweight, and easily processable. In terms of sustainability, these synthetic fibres have advantages and disadvantages depending on the application. One advantage is that these materials are strong and durable in general, thus they can last for a long time, which reduces the need for frequent replacements, as in long-lasting products durable materials are required. Additionally, some of these materials can be recycled, which can help to reduce waste from ending up in landfills, however, for example nonwovens used in some medical applications, for example in hospitals, are mostly still burned after their end-of-life. However, these materials are not bio-based or biodegradable, so if these materials are used in single-use applications or products that are not intended to be used for a long time, they can end up in landfills, and it takes a long time to break down in the environment, increasing pollution and possibly leaving microplastics in the nature, or the other common way of incineration of the materials in the products' end-of-life is not sustainable on a long run either. The application areas of these fossil-based fibres are wide, and they are used for example in hygiene, filtration, protective clothing, automotive, household, and construction sectors.

Table 2. Strengths and weaknesses of traditional synthetic fibres and polymers in nonwovens.

Strengths	Weaknesses
• Typically, high tear resistance, especially compared with natural fibres and MMCFs (strong and durable) • Naturally water-resistant (hydrophobic, beneficial in some applications) • High chemical and heat resistance • Easy maintenance of end products (strong, stain resistant) • Can be processed with wet, dry, and direct processes • High mechanical properties create potential for these fibres to be used in new advanced materials, such as for use in aerospace industry • If can be recycled → lowers the need of using virgin materials • Can be processed with either mechanical, thermomechanical, or chemical recycling • Most synthetic fibres very affordable compared to natural or MMCFs • If regulations push towards change of single-use to multi-use or long-lasting materials, synthetic fibres can perform well even after several uses or using for a long time • Potential to use recycled fibres as secondary raw material for example in thermal insulation boards in building applications • Potential to waste materials in nanocomposites for example in automotive sector • Potential to utilize recycled *disposable* technical-grade PP textiles in the function of matrix-phase in sustainable building materials, such as insulation • As recycling technologies continue to improve, it may become easier to recycle nonwovens made of synthetic fibres	• None/low moisture absorption (unfortunate in absorbent products, needs additional surface treatment) • Low hygroscopicity → Difficult to dye (polyamide) and prone to static electricity, need of additional surface treatment • UV and sunlight can degrade mechanical properties → addition of a UV stabilizer often needed • In recycling process of polyester waste, shredding into smaller fractions hard due to high tear resistance of the material → can result in temperature rise which melts the material • Degradation of degree of polymerisation (DP) in recycling process → losing of essential mechanical, thermal and chemical properties • Fossil-based, non-renewable • Not biodegradable • Mainly energy-intensive production process (water, electricity) • The use of synthetic fibres has been under concern the last years due to microplastic pollution • SUP directive reducing the use in some applications (microplastic issue)

In addition to these synthetic fibres from fossil-based sources, also similar thermoformable materials can be created from **natural sources**, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), from which PLA can be produced from fermented plant starch, for example from corn or sugarcane, and PHAs are produced by numerous microorganisms making these materials bio-based and (industrially) biodegradable.

Table 3. Strengths and weaknesses of novel bio-based plastics (PLA, PHAs) in nonwovens.

Strengths	Weaknesses
• Thermoformable polymers → can be processed with direct processes, together with other processes • Can be used as a strengthening binder with other fibres • High UV resistance • Research and development (R&D) can lead to improved materials, or even new bio-based plastics • Bio-based and biodegradable (in industrial conditions) • Can be used as a binder reducing the use of fossil-based binders or chemicals • Low water consumption in processing compared to many other raw materials • Regulations aiming at reducing the use of fossil-based plastics (e.g., SUP) • Increased demand for sustainable products → investment and growth	• Lower mechanical strength and toughness compared to conventional fossil-based plastics → may limit their use in some applications • Competition with traditional, fossil-based plastics (fossil-based are low in cost and very durable and strong) • Industrially biodegradable, i.e., needs specific conditions to degrade even though described as biodegradable (degradation at over 155°C) • collection and disposal of bioplastics → lack of infrastructure / not widely available • The lack of knowledge (both companies and consumers) → can limit adoption and use of bio-based plastics • Higher production cost compared to traditional fossil-based plastics

Regenerated cellulose-based fibres are also an important group of man-made fibres to produce nonwovens. These fibres include different cellulose-based fibres, for example viscose, which is a regenerated cellulose fibre that is very commonly used fibre in textile sector. Viscose is not the most sustainable material to be used due to the use of harsh chemicals[a], water and energy, but viscose can be seen as more sustainable alternative compared to fossil-based plastics, and for example cotton. Viscose is widely used in nonwovens as viscose is very affordable material with good mechanical properties, and the viscose fibres have excellent water absorbency properties, which is beneficial especially in hygiene applications. Many more sustainable man-made regenerated cellulose-based fibres have been invented, such as lyocell, which is more expensive to process compared to viscose process, but the advantage of the lyocell process is the more environmentally friendly process, in which highly toxic carbon disulphide is not used, and instead, more sustainable chemical[b] is used as a solvent. Other innovations including more sustainable processes to produce regenerated cellulose-based fibres include the use of, for example, ionic liquids or other more sustainable solvents, and the innovations involve, for example, Ioncell®, Spinnova®, and Infinna™.

[a] In viscose process, a treatment with carbon sulfide is used to get a xanthate derivative and converted to viscose
[b] N-methyl morpholine N-oxide (NMMO)

Table 4. Strengths and weaknesses of man-made cellulosic fibres (MMCF) in nonwovens.

Strengths	Weaknesses
• High moisture management properties – good moisture absorption (hygroscopicity) and moisture release properties → suitable for use in applications that need to manage moisture, such as wipes and hygiene products • High comfort and softness • High strength and tenacity (Lyocell) • Bio-based, biodegradable • Low water consumption compared to some other natural fibres (for example cotton) • man-made cellulosic fibres can be more sustainable alternative to replace synthetic fibres in some applications → creates opportunities in markets where sustainability is a priority • Increased demand for hygiene products → creates opportunities for these fibres to be used • R&D → new innovative applications for the use of these fibres in areas such as medical textiles and hygiene sector	• Low wet strength compared to synthetic fibres and some natural fibres, for example cotton • Not as heat-resistant as some synthetic fibres → limits use in high-temperature applications • Viscose process includes use of harmful chemicals • Lyocell process is expensive compared to many other raw materials' processing • Thermoset → cannot be melt-processed • Higher density than many synthetic fibres

2.1.3 Recycled fibres

One possible source of raw materials for nonwovens could also be **recycled fibres or materials** to replace the use of virgin, or oil-based materials with a more sustainable choice. Short overview of textile fibre recycling methods is included in Figure 3.

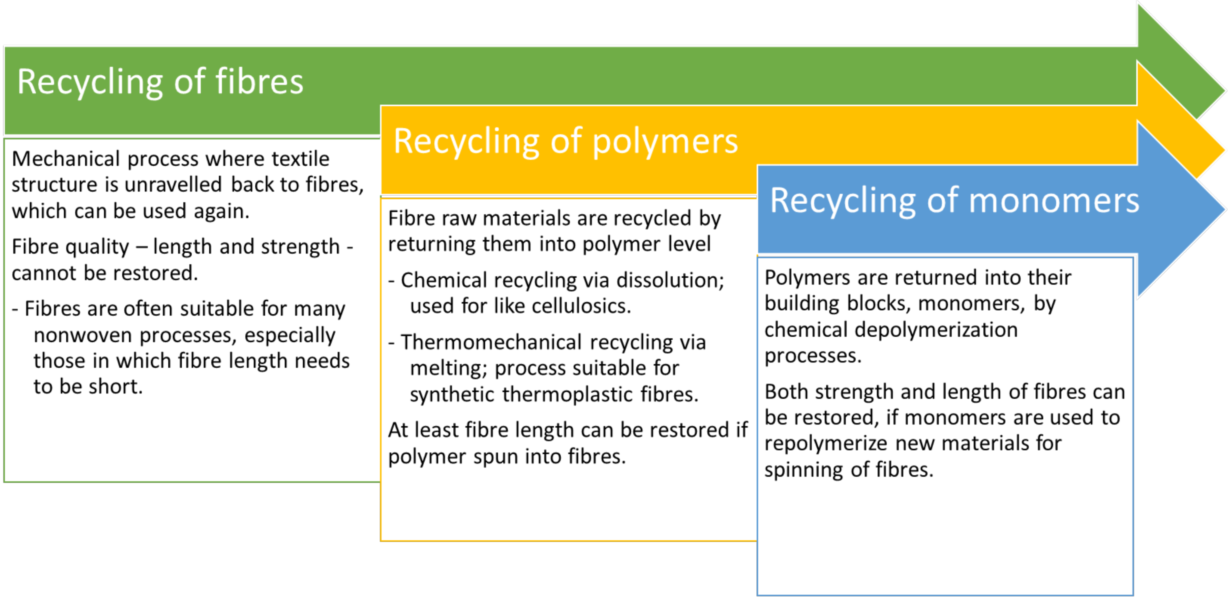


Figure 3. Overview of textile fibre recycling technologies.

Textiles, for example, from apparel can also be used to create nonwovens by mechanical recycling. In mechanical textiles are shredding into smaller pieces, which are opened into threads, and fibres. Such recycled fibres can be used as such or as mixture with virgin fibres in nonwovens made by carding or air-laying and bonded by needlepunching. As an example, wool from mattress fillings and duvets have been formed into nonwovens to make lower-cost applications, such as insulation and oil sorption products[8]. and recycled fibres are also used, for example, in nonwovens in automotive sector, especially in boot linings and carpeting[9].

In addition to mechanically recycled fibres, also thermo-mechanically and chemical recycling could be used, although chemical recycling is still not done in a larger scale, and it takes time before used at a larger scale. However, chemical recycling provides possibility to restore quality similar to virgin materials. Industrial and post-consumer waste can be reformed into new raw materials via thermo-mechanical process by remelting and reprocessing. One example of this recycling type is recycled PET (rPET) from PET bottles to form new products. This way, the raw material (PET) is downcycled from plastic bottles to nonwovens, and since PET cannot be recycled back into plastic bottles from nonwovens, this creates a need of using more virgin materials to produce plastic bottles. However, the use of rPET is quite marginal at the moment, and mechanically recycled textile fibres are at the moment more commonly used to produce nonwovens from recycled materials in the EU. Especially now that the European union (EU) has set new legislation which obliges the countries belonging in the EU start collecting textiles by 2025[10], more recycled fibres and materials for textiles are going to be possible to be used for new products.

Table 5. Strengths and weaknesses of recycled fibres and polymers in nonwovens.

Strengths	Weaknesses
• Lower the need of using virgin materials • Repurpose fibres from previously discarded materials → gives value to recycled materials previously seen as waste • Using recycled materials or fibres aligns with sustainability initiatives and can enhance the market appeal of the end products as increasing amount of consumers are making more eco-friendly choices • Mechanically recycled (textile) fibres – rather easy and energy-efficient process • Possibility to restore quality and hygiene level equal to virgin materials with chemical recycling	• Some applications need high mechanical properties or hygiene level → not suitable for all applications at the moment (mechanically recycled) • Lower mechanical properties (strength) compared to virgin materials (mechanically recycled fibres) • Linting and raw material fluctuation • Hygiene level of (especially post-consumer) materials • Finishing agents, other chemicals many times need to be removed → needs energy and/or use of chemicals • Chemical recycling still not done in a larger scale (technology still taking first steps) → takes time before used at a larger scale • If recycled materials taken from other product loop (for example rPET from bottles → downcycling), new virgin materials needed for other products (bottles) • Some recycling methods (chemical) are energy-intensive

2.1.4 Other raw materials

Other fibres used in nonwovens include, for example, glass and carbon fibres. In general, these fibres are strong and durable, and they can be used to create nonwoven fabrics with a wide range of properties. Some common applications made from these fibres include insulation materials, fireproofing products, and abrasive pads.

2.1.5 Comparison of fibres

Table 6. Comparison of the raw material categories by environmental impacts. The chart is modified from[11].

★★★ Very positive impact, ★★ Moderate impact, ★ Negative / Not good impact, N/A Not applicable, - Insufficient data

Factor	Natural fibres		Man-made fibres		
Factor	**Cotton**	**Wool**	**MMCF (e.g., Viscose, Lyocell)**	**Bio-based plastics (e.g., PLA, PHAs)**	**Synthetic (PES, PP, PA)**
Water consumption[11]	★	★★★	★★	★★★	★★★
Energy consumption[11]	★★	★★★	★★	★★	★★
Greenhouse gas emissions[11]	★★	-	★★★	★★	★
Use of chemicals in finishing[11]	★(★)	★(★)	★★	★★(★)	★★(★)
Biodegradability	★★★	★★★	★★★	★★(★)*	★
Land usage[11]	★	★	★★	★★★	N/A

* Mainly in industrial conditions

2.2 Web formation methods

Nonwovens can be characterized by the web formation processes, which are separated into three different categories – dry-laid, wet-laid, and direct-laid processes. Staple fibres can be processed into webs using dry (air laying and carding) and wet methods (traditional and foam). Direct laying methods (spunlaying and meltblowing) refer to processes in which nonwoven web is produced directly from melted thermoplastic polymers, or from polymer solutions. Web formation technologies are shown in Table 7, in which is shown also what kind of raw material types can be used with the different web formation technologies.

Table 7. Web formation technologies for different raw materials.[2,5,12]

Raw material type	Wet laying		Dry laying			Direct laying	
	Traditional	Foam	Air laying		Carding	Spun-laying	Melt-blowing
			Drum former	Air card			
Short staple fibre (<5 mm)	X	X	X	(X)			
Longer staple fibres (up to 20 mm)		X		X			
Textile staple fibres (up to 150 mm)					X		
Pulp	X	X	X				
Filament						X	X

2.2.1 Dry-laid methods

Two dry-laid methods, carding and air laying, are available to produce nonwoven fabrics. These both methods are well established and commercially used methods. Both are suitable for primary/virgin and secondary/recycled fibre materials.[2,5]

Carding

In carding, fibres are opened, separated, and combed by card into thin fibre webs. Such thin webs are typically layered into thicker structures, where layers can be oriented in the machine direction (MD) or cross-laid into zig-zag batts. In the carding process, staple fibres with wide range of lengths can be used, from typically 30 mm to 100 mm, making carding a versatile web formation method to be used. The grammage of the final product can vary a lot from 10 to 250 g/m^2. The production speed of carding can be up to 250 m/min making it a fast process to produce nonwovens.[2,5]

Carding has some advantages compared to many other web formation techniques, for example, blending of different fibre length types is possible and relatively easy with carding. Also, the fibres or fibre mats can be layered to achieve different characteristics. With carding, nonwovens with high softness can be achieved which is beneficial especially in hygiene products. Although different fibre lengths and types can be blended with carding, very short fibres, i.e., fluff or wood pulp are not feasible in carding as dusting and fibre transfer will be a major problem. Some challenges with carding are that carding produces highly aligned webs, and additional treatments are needed to re-orient fibres to recover cross-directional strength, if this is needed. Carding allows creating different kinds of nonwovens, and carded nonwovens can be *disposable*, such as hygiene products and wipes, or durable, such as apparel linings and insulation.[2,5]

Air laying

In air laying technologies, opened fibres are fed into the strong air stream which carries them onto the permeable conveyor as randomly oriented batt is formed. The fibres used in air laying are usually relatively short, but depending on the air laying technology, the fibre length can vary. In *airlaid* technology, in which drum former is used, fibres have to be relatively short (typically less than 5 mm) in order to get fibres through the holes of the drum former and form a sheet. *Airlaid* technology, in which drum former is used, is sometimes called also as dry paper making. In another air laying technique, *airlay* technology, fibres can be longer. Both air laying technologies are compatible with a variety of generic fibre types including natural and synthetic fibres, but depending on the used technology, the fibre length affects the processability.

Air laying technologies can deliver fibre webs with high isotropy, high porosity, and high loft, if required. As a result, a highly isotropic nonwoven product with a lower grammage of usually around 50–100 g/m^2 is produced.[13] Although, production of very lightweight (less than 45 g/m^2) hydrophobic products are challenging to produce with air laying technologies, and production speed of air laying technologies is usually rather slow (30–40 m/min). Nonwovens made with air laying technologies are used in many different applications depending on the used fibres and the bonding methods. In general, as these nonwovens usually have high porosity and high absorbency, these characteristics are beneficial in absorbent nonwovens, such as wipes, diapers, napkins, and medical nonwovens, but also some filtration and insulation applications.

Table 8. Strengths and weaknesses of dry-laid methods (carding, air laying).

Strengths	Weaknesses
Both • Suitable for monomaterials and blends • Recycled fibres can be used (depending on the length) • Web weight can be adjusted (80–1000 g/m^2 carding, 50–8000 g/m^2 air laying) • Wide range of material properties can be achieved from many types of fibres when different layering patterns and bonding methods are used • Lower capital investment compared to for example wet laying • Dry method, no water and relatively low energy use **Carding** • Produces high quality webs at relatively high production speed (125–600 m^2/min) • Multiple layers can be made to achieve different performance characteristics **Air laying technologies** • Ability to blend different fibre types & lengths during the process • Nonwovens have lower density, higher softness, and higher isotropy compared to carded nonwovens in general • Webs can have very high porosity and absorbency (beneficial for example in absorbent products and medical items)	**Both** • Opening of fibres have to be done very well in order to avoid tangled clumps or fibre flocks • Uncontrolled static electricity, low fibre-to-fibre cohesion, permanent fibre elongation → Fibre breakage and poor yield • Lower throughput rate than spunlaid nonwovens (used for same applications) **Carding** • Different carding processes for different fibre lengths • Processing of short fibres is challenging, as especially dusting is an issue • Use of recycled fibres may damage cards if containing unopened structures and/or metallic residues • Older installed equipment base **Air laying technologies** • Production rate is usually rather low (30–40 m/min) • Demand of single-use nonwovens is rising → Air laying is slower process, cannot be used for very fast mass production at the moment
Example applications: • ***Disposable*** **–** for example absorbent products, such as wipes, napkins, and medical nonwovens, but also other hygiene and filtration • ***Durable*** **–** for example apparel and shoe interlinings, support for plastics, packages, tea bags, etc., high-loft products for mattress insulation, etc.	

2.2.2 Wet-laid methods

Traditional wet laying is similar to traditional papermaking process; thus, it could also be described as modified papermaking process, and foam laying is modification of that. Traditional process is commercially used, while foam laying is still reserved for specialty applications, i.e. fibre glass mats.

Traditional wet laying

In traditional wet laying process relatively short staple fibres are dispersed into water often as a blend with wood pulp or viscose with high dilution. The solution is collected as almost random orientation onto conveyor for water removal. After dewatering, the used water is filtered and recycled, and the web is dried, resulting in a highly isotropic web. For technical applications, usually after formation of wet-laid web, the web is chemically bonded with impregnation process for filtration fabrics and technical textiles, whereas in hygiene applications hydroentanglement is more preferred way. For hygiene applications internal strength additives or mechanical bonding methods, such as hydroentanglement are usually preferred.

One benefit of wet laying compared to many other web formation processes is that wetlay produces very high uniformity. Wetlay can also be used with very short fibres, for example wood pulp, which are generally not suitable to use in many other web formation processes, can be processed easily with wet laying. In addition, the production rate of wet laying is very high, and the uniformity of the formed sheets is high. Although, the process requires high capital investments, and wet laying is quite energy intensive, since high dilutions of fibres and water are created, and high volumes of water are drained from the web after web formation or need to be evaporated. Wetlaid nonwovens have a lot of different applications, such as towels, hygiene products and filtration, and they are also used in many more technical applications, such as glass fibre mat for roofing, insulation materials and battery separators.

Foam laying

Foam laying follows similar principles to traditional wet laying, but instead of water, aqueous foam is used as the transfer media. In foam laying, the fibre lengths and consistencies can be higher compared to wet laying, since air bubbles surround the fibres preventing bundling, or flocculation of the fibres. Using foam also leads to good formation of the produced materials, i.e., very homogeneous materials even with lower basis weights. The typical air content for foam-laid structures is from 40 to 70%.

Compared to wet laying, using foam can improve dewatering in forming section, which can lead to lower drying time, resulting in lower energy consumption. Also, because of improved dewatering phase, there is a lower need for the use of retention chemicals. Using the foam instead of water also provides a variety of possibilities for material engineering, as the air content and final material density can be adjusted in the process. Different lengths of fibres can be rather easily mixed with foam laying, and this enables using of longer fibres than for example in the traditional wet-laid process. Also, compared to air-laid process, foam-laid process can be run with higher production speeds.[14]

A challenge in the process is that in the process, there are many interactions between fibres and the foam, such as stability, bubble size and rheology of the foam, and adding even more components in the structure, such as chemicals, can make it even more complicated, and it is important to understand these interactions in the foam forming process.[14]

Foam laying could be utilized to produce many kinds of nonwovens for example in hygiene applications, but currently it is mainly utilized for specific technical textiles.

Table 9. Strengths and weaknesses of wet laying methods (traditional, foam).

Strengths	Weaknesses
Traditional • Almost all types of fibres are suitable • Processing of very short fibres possible (for example natural wood pulp) • With stiffer fibres the consistency can be higher • High productivity (production rate 750–3000 m²/min) **Foam** • The dry content of the head box furnish can be very high → Lower need of water consumption • Using foam can improve dewatering in forming section → Lower drying → Lower energy consumption • Less dewatering → Lower need for the use of retention chemicals • Wide variety of fibre lengths – from nanoparticles up to 200 mm long fibres • Enables using of longer fibres than in the traditional wet-laid process • High bulk, wide range of bulk-strength relationships • Multi-ply structures possible to be produced **Both methods** • Low basis weights possible • Isotropic as well as anisotropic structures can be produced • The uniformity of the formed sheets is high	**Traditional** • If flexible fibres are used, typically the length has to be less than 25 mm in order to reduce the entanglement of fibres • Energy-intensive method • High dilutions used → High water consumption → High drying costs • Technologies using less energy is needed → For example foam laying can replace (at least part of) using wet laying **Both methods** • Very capital intensive • Limited by cost and availability
Example applications: • ***Disposable*** – for example hygiene products, filtration • ***Durable*** – for example (replacement for) glass fibre mat for roofing, insulation materials, etc.	

2.2.3 Direct-laid methods

Direct-laying refers to methods where nonwoven is made directly from polymer granulates. Spunlaying and meltblowing are both mature technologies and widely used in nonwoven manufacturing.

Spunlaying

Spunlaying is the largest nonwovens' web forming process, covering almost half of all nonwovens consumed, and spunlaying process has been estimated to grow at the highest rate of all web formation processes the upcoming years [7]. In spunlaying, polymer granulates are directly converted into filaments. The polymer granulates are fed into an extruder, in which the granulates melt, and are transferred to spinpack. In spinpack, the polymer melt is distributed into a spinneret that forms continuous filaments, and the filaments are drawn and cooled to promote desired crystalline structure. Cooling of filaments is accomplished by blowing air stream through the filaments, which are then transported to the downstream discharge channel. The filaments are swirled and placed on a belt to form a randomly oriented nonwoven material.

Spunlaying is currently very large and important web forming technique in the nonwoven industry. Advantages of spunlaying process are especially the cost effectiveness and performance of the products. New solutions are being applied to spunlaying process, such as making a shift from oil-based polymers to bio-based and biodegradable polymers, such as PLA (polylactic acid) or PHAs (polyhydroxyalkanoates) or focus on working on more efficient recycling of the used materials. Spunlaying is used for both, disposable and durable applications. The main nonwoven segments in which spunlaid nonwovens are used, are hygiene, medical, packaging, agriculture, automobile, and geotextile sectors.

Meltblowing

Meltblowing is similar process to spunlaying, but instead of producing continuous filaments, the filaments are exposed to hot high-velocity air streams in the extruder orifice, which cuts the filaments resulting in shorter microfibers of various lengths that are randomly oriented. Compared to spunlaying, meltblowing is slower process compared to spunlaying.

One advantage of meltblown nonwovens is formation of a network consisting of fibres with low fibre diameter, which is beneficial in filtration applications, for example face masks, which production has increased significantly during the last years. Other good properties of meltblown webs are high barrier and wicking properties. Since structure compose of thin microfibers, the strength of the web is weaker compared to spunlaid nonwovens, but usually meltblown and spunlaid nonwovens are also layered to obtain a strong and high opacity material, called as SMS (spunlaid-meltblown-spunlaid) structure. As in spunlaying, also in meltblowing only thermoformable polymers or fibres can be used, with low viscosity and high melt flow index, which limits the possible raw materials to be used in this web formation process. As in spunlaying, also in meltblowing the main segments in which meltblowing is utilized, are for example in hygiene and medical sectors.

Table 10. Strengths and weaknesses of direct methods (spunlaying, meltblowing).

Strengths	Weaknesses
Both methods • Processing of new bio-based thermoformable polymers: PLA, PHAs, etc. • Cost-effective process • Highest throughput rate of all nonwovens processes • High performance of the products • Shortest route from polymer to fabrics (eliminates steps in between, one-stage-process) è reduction of cost and increase of production • a wide variety of nonwovens can be formed: very lightweight and flexible to heavy and stiff structures • Layering is possible → basis weight can be adjusted easily with layering **Meltblowing** • Formation of a network consisting of fibres with lower diameter and high surface area → Beneficial in filtration and insulation applications • The partially molten fibres fuse together when the web is formed → seldom separate bonding is needed	**Both methods** • Methods applicable only to thermoplastic polymers • Most of thermoplastic polymers are currently fossil-based • SUP directive may apply • Mainly used to produce fossil-based products → Need of more sustainable routes • A lot of parameters affect the final structure (such as polymer characteristics, extruder conditions, geometries, die conditions…) • (New) energy-efficient technologies are needed **Meltblowing** • High energy and consumption (extrusion, hot air stream, thermal bonding) - also slightly less in spunlaying • Low to moderate web strength due to very short and thin fibres
Example applications: • ***Disposable*** – for example hygiene, medical (surgical gowns, masks, gloves, caps, shoe covers, wound dressings, plasters…), filtration, adsorbents • ***Durable*** – for example applications in agriculture, automobile, geotextiles, filtration, acoustic insulation	

2.2.4 Other methods

There are also some niche technologies producing nonwovens and/or nonwoven like materials.

Electrospinning

In electrospinning, polymer solution is exposed to static electric field which stretches it into thin filaments which can be collected as sub-µm nonwoven web. The diameter of resulting filaments ranges from a few nm to a few mm, so very thin filaments can be produced. Different polymer solutions – synthetic polymers, biopolymers, blends, or composites can be processed with electrospinning, and also for example nanoparticles can be also used together with other fibres. The nonwoven web formed after electrospinning in general has a high specific surface area. There is a wide range of applications especially in technical applications, such as filtration, sensor technology, and in drug delivery systems.[15]

Flash spinning

In flash spinning, polymer solution is extruded into a film-like structure, which gets fibrillated when solvent is removed by very fast evaporation. This happens in one phase before the solution is flashed from the nozzle. When the polymer solidifies, a structure composed of very fine continuous filaments is formed.

Flash spinning was invented first by DuPont, the leading synthetic materials' manufacturer in the world, for their Tyvek nonwoven fabric, used mostly in protective clothing[16].

Film fibrillation

In film fibrillation, polymer film, produced either by melt extrusion or by polymerization, is patterned and then stretched into fibrillated structure.[17]

2.2.5 Comparison of web formation technologies

Table 11. Comparison of web formation technologies from environmental point of view. Comparison made according to information from literature sources[2,5].

★★★ *Highly positive*, ★★ *Somewhat positive*, ★ *Moderate*, × *Low / Negative*

Factor	Carding	Air laying	Wet laying		Spunlaying	Meltblowing
			Traditional	Foam		
Water consumption	★★★	★★★	×	★	★★★	★★★
Energy consumption	★★	★★	×	★	★★	×
Ability to blend/use different fibre lengths & types	★★★	★★	★★	★★	★	★
Production speed	★★	★	★★★	★★	★★★	★★

2.3 Web bonding

Nonwoven webs in most cases need to be bonded to achieve high strength characteristics. Bonding methods include mechanical, thermal, and chemical methods, as described in following chapters.

2.3.1 Mechanical bonding

Mechanical bonding methods are based on mechanical entanglement of fibres.

Needlepunching

In needlepunching, the fibres are mechanically intertwined by needle felting with serrated needles. Basically, barbed needles are inserted through the web to facilitate the entanglement of the fibres. With each punch some fibres from the surface are pushed onto the other side forming interlacing. This method condenses fabric and forms strong felt-like materials. This bonding technique is suitable also for combining different materials together. The characteristics of the final material can be adjusted by the depth of penetration of the needles together with density of the needlepunching. In needlepunching, both natural and synthetic fibres are used, but the most typical fibres used are long air-laid fibres or spunlaid webs. Needlepunching is utilized to produce bonded structures that are used mostly in filtration, geotextiles, floor coverings, and automotive headliners.

Spunlacing or Hydroentanglement

In spunlacing, mechanical intertwining of fibres is done by high-pressure water jets instead of needles. The fine water jets penetrate the web, hit the conveyor belt, and bounce back resulting in entanglement of the fibre web. Compared to needlepunching, fluffier materials can be produced. The produced materials are lightweight, fluffy, soft, and flexible. In spunlacing/hydroentanglement, different types of staple fibres and fibre blends can be used that are made by carding, air laying or wet laying, but it is also suitable for spun-laid webs. The most used fibre blend used in spunlaced fabrics is mix of polyester and regenerated cellulosic fibres, for example viscose. One needed property of the fibres is the high enough flexibility in order to intertwine the fibres by hydroentanglement process.

Spunlacing allows to produce soft products of identical or higher strength compared to chemically bonded nonwovens, which is beneficial in producing more user-friendly nonwovens, such as hygiene and cosmetic products without addition of chemicals, offering good skin tolerance, but also to decrease the environmental impacts of the manufacturing process. In spunlacing process, a large volume of water is used. Water can be re-used, but recirculation and filtration to remove any contaminants before entering back to the injectors covers most of the total costs of spunlacing process[18]. Still, the spunlacing process has several advantages as a bonding method, such as reducing energy consumption per kilogram of raw material used and reducing material losses together with water consumption if optimized filter systems are used. Also, the process lines have minimal maintenance requirements compared to many other methods' process lines. The typical applications of spunlaced nonwovens are wipes, protective clothing liners, filtration, garment, and leather interlinings, and automotive nonwovens.

Table 12. Strengths and weaknesses of mechanical bonding.

Strengths	Weaknesses
• Natural and synthetic fibres or fibre blends can be bonded • No chemicals are needed – bonding happens by mechanical interlocking of fibres • Strong webs can be formed • Hydroentanglement could be possible to replace (harsh) chemical binders still keeping the high characteristics (softness, absorbency, strength, flexibility)	• Certain characteristics are needed from the raw materials – flexibility for hydroentanglement and high length for needlepunching • High water consumption (hydroentanglement) • High energy consumption because of mechanical work

2.3.2 Chemical bonding

In chemical bonding, chemical bonding agents are added into web. Properties of web depends on how chemical agent is applied and how much of agent will remain in the web; binders form a network of interlocked fibres, and the binder can be spread throughout of the structure or in certain areas, depending on the required end-use. Amount of these agents can be up to tens of percents, and they can also have other functional purposes. The type of the binder also affects the sustainability of the formed web – recyclability and/or biodegradation at the end-of-life of the product. Chemical bonding is a very widely used bonding technique as it is a versatile technique with a variety of binders available, and the final properties can be adjusted together with the durability of the products.

When the binders started to be used, natural binders, such as starch and natural rubber, were used, but nowadays synthetic polymers are the most used binders in the industry because of their low price, processability and availability. The most common binders used are latexes, dispersions of specific polymers in water. The interest towards more environmentally friendly choices has increased during the last years, thus finding more biobased, recyclable, and/or biodegradable options is needed.

In addition to bonding of the nonwoven webs, binders can be used to already bonded webs to provide additional functionalities, such as improve wet strength, visual appearance, fire retardancy or to control wet pick-up. Thus, chemical bonding is quite commonly used as a combination bonding with some other bonding method in order to modify the properties of the produced fabric.

The production speed is limited due to the drying and curing stage, also chemical bonding is an energy-intensive process as the heat required to evaporate water from the binder takes more time and energy compared to thermal or mechanical bonding processes.

In chemical bonding, different kinds of bonding methods can be used:

Impregnation

In impregnation (or saturation), web is impregnated, i.e., put through a liquid bath of chemical bonding aid, typically acrylic or polyvinyl alcohol based, and then squeezed between nip rollers or a padding machine. This way, the material is fully treated with binder.

Foam

In foam bonding, binder is dispersed in foamy structure by agitation, and less water can be used. Although, when liquid Is replaced with foam, there will be less binder inside the structure compared to saturation. Foam can also be applied only on one side.

Printing

Binder can be applied by printing using, for example, transfer (gravure or screen) and digital printing. Patterning is then possible, and there will be more binder on surfaces than in bulk.

Spraying

If binder is sprayed, there will be more binder on surfaces than in bulk, forming usually more inhomogeneous bonding compared to other bonding methods.

Table 13. Strengths and weaknesses of chemical bonding.

Strengths	Weaknesses
• Use of bio-based binders • The final web can be adjusted depending on the chemical composition and amount of the binder • Bonding can provide added functionalities (for example fire retardancy, improved wet strength, visual appearance) • Foam bonding allows lower water consumption	• Production speed is limited due to the drying and curing stage • High energy and water consumption (Curing is necessary, drying) • The SUP Directive might lead to reduction or ban of fossil-based binders

2.3.3 Thermal bonding

In thermal bonding, a thermoplastic component is needed in order to bind the structure with heat; heat is applied until the thermoplastic component melts, and forms bonding regions, which are fixed by subsequent cooling. The formed bond is a physio-chemical bond at the interface of two different materials. In thermal bonding, the amount of thermoplastic binder component varies usually from 5 to 50% on weight of fibre, depending on the needed requirements of the final product. The binder component used in thermal bonding has lower melting point than other fibres used in the structure in order for the binder component to soften and bind the structure without melting of other parts. The commonly used base fibres can be natural fibres, synthetic fibres, metallic fibres, but also the core of the bicomponent fibre, in which the sheath component act as the binder part.

The advantages of thermal bonding are for example lower energy costs and environmental impacts compared to chemical bonding, since thermal bonding requires lower thermal energy due to the absence of higher water evaporation during bonding phase, no latex binders are required, and thermal bonding also requires less expensive machinery. With thermal bonding, products with relatively soft feel and high bulk with good uniformity can be obtained. Also, thermal bonding method is suitable to be used with all web formation methods if thermoplastic binder component is added into the structure.

There are different methods to apply heat into the web to bond the web – calendering, hot air, and ultrasonic.

Thermal calendering

In thermal calendering, a fibrous web containing thermoplastic parts is passed through a heated calender nip, in which two rolls are pressed against each other. Both rolls are heated usually to a temperature which slightly exceeds the melting point of the thermoplastic components to ensure sufficient softening of these parts. After heating and softening, bond sites are formed in the structure, and cooling leads to solidification and bonding of the structure. Calendering is usually used to light-weight webs (25–30 g/m2) for medical and hygiene applications, or medium-weight webs (100 g/m2) for interlining and filtration applications, but also for different kinds of geotextiles.

Hot air

Air with high temperature is used to melt the thermoplastic component. Hot air is suitable or used characteristically in heavyweight webs to result in uniform bonding throughout the web.

Ultrasonic

Ultrasonic bonding utilizes high frequency vibration to transfer heat to restricted areas in the web to ensure thermal bonding. In this bonding technique, a nonwoven web is compacted between an embossed patterned roller, also referred to as a rotary anvil, and an ultrasonic horn. The horn vibrates at high frequency, resulting in submitting thermal energy into the web above the highest points of the rotary anvil, which results in melting and compression of the web in those areas above the highest points. This technique leads to well defined bond points and excellent appearance of the nonwoven fabric. The disadvantage of ultrasonic as a bonding method is transformation of stable vibrational energy across the full width of wider fabrics. This usually requires many overlapping horns, which might show as visible lines of overlap in the final product. The product obtained after ultrasonic are strong, soft, breathable, and absorbent, and are suitable for patterned composites and laminates, for example quilts and outdoor jackets.

Table 14. Strengths and weaknesses of thermal bonding.

Strengths	Weaknesses
• Suitable with all web formation methods in which thermoplastic component is included (not with just natural fibres) • Less expensive machinery compared to chemical binding • Soft, high bulk and high uniformity products can be obtained • Lower energy costs compared to chemical binding (no need for water evaporation)	• Cannot be used with a structure which consists of just natural fibres • Need of energy (heat)

2.3.4 Other bonding methods

Stitching

In stitch bonding, binding is done with modified warp knitting machine. Yarn forms chain or tricot stitches. Used typically for denser fabrics.

Solvent treatment

Solvent treatment can be also considered as chemical binding method. In this method web is treated with solvent which softens fibre surfaces and cause them to adhere. No additional binding agent is needed since bonding occurs on fibre crossings.

Enzyme treatment

Using of enzymes can be used as a tool to functionalize the fibre surfaces which contain lignin to reduce the use of binders. In enzyme treatment, laccases are the most commonly used enzymes, but also peroxidases are enzymes which have been used in enzyme treatment.[16]

Plasma treatment

Plasma treatment is a technology to enhance inter-fibre covalent bonding, as using plasma introduces free radicals onto fibres' surfaces.[16]

2.3.5 Comparison of web bonding technologies

Table 15. Comparison of the web bonding technologies from environmental point of view. Comparison made according to information from literature sources[2,5].

★★★ *Highly positive*, ★★ *Somewhat positive*, ★ *Moderate*, × *Low / Negative*

Factor	Mechanical		Chemical	Thermal
	Needlepunching	Hydroentanglement		
Water consumption	★★★	★★	★	★★★
Energy consumption	★★	★★	×	★
Use of (synthetic) chemicals	★★★	★★★	×	★★
Suitability to be used in combination with different web formation technologies	★★	★★	★★	★★

2.4 Finishing

The finishing of nonwoven fabrics is an important part of producing the final product to improve the appearance, performance, or other characteristics of nonwoven fabrics. The selection of finishing technique depends on the application and desired functionalities.

Common finishing treatments for nonwovens include calendering, which smooths and compacts the fabric; coating, which adds a layer on the fabric that can improve for example nonwovens' durability; and embossing, which creates a textured pattern on the fabric. Other finishing treatments include for example fire-retardant treatments, which reduce the flammability of the fabric, and antimicrobial treatments, which inhibit the growth of bacteria and other microorganisms, or hydrophobizing treatments making the fabric more water-resistant.

3. Nonwoven segments and their requirements

Nonwovens can be separated into two major sectors – *disposable* and *durable* nonwovens[c]. *Disposable* nonwovens are usually single-use products, such as baby diapers, medical nonwovens or wet wipes, or other products that last relatively short time. *Durable* nonwovens are long-lasting products with lifetime of months to years, or multi-use products, such as air and gas filtration, floor coverings and construction applications. The focus in *disposable* nonwovens is more on consumer products, whereas *durable* nonwovens are used more in industrial applications.

In this chapter, the different nonwoven segments and the most important requirements that must be considered for these segments are explained on a rather general level to gain understanding on what are the needs in different applications. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

3.1 Disposable nonwovens

During the last years, the production and consumption of *disposable* nonwovens have grown a lot more compared to durable nonwovens, in which we have seen even reduction of production and consumption in some areas, especially due to the Covid-19 pandemic, which rapidly increased the markets of disposable face masks and antimicrobial nonwovens (for example disinfecting wipes). Many *disposable* nonwovens are complex or multi-component structures, since many different additional functionalities are needed, such as absorbance and anti-microbial properties. As an example, diapers can have up to eight different nonwoven layers each offering different functionalities, meaning the use of a variety of web forming techniques together with different raw materials.

3.1.1 Hygiene applications

Hygiene applications are the largest group of *disposables*, and all the other, nonwovens mainly because of the high consumption of baby diapers and feminine hygiene products. Other examples of nonwovens in hygiene sector are for example incontinence products, nursing pads and toddler training pants. Nonwovens are used in many parts of hygiene products, such as top sheet or cover stock, acquisition layer, and core wrap. What unites many of these products is the use of superabsorbent polymers (SAP) in the fabric which are necessary to absorb liquids efficiently and quickly. SAP[d] is a material which can absorb up to 300 times its weight of aqueous liquid, but it is a material which does not release the liquid easily, making use of SAP beneficial in hygiene applications.

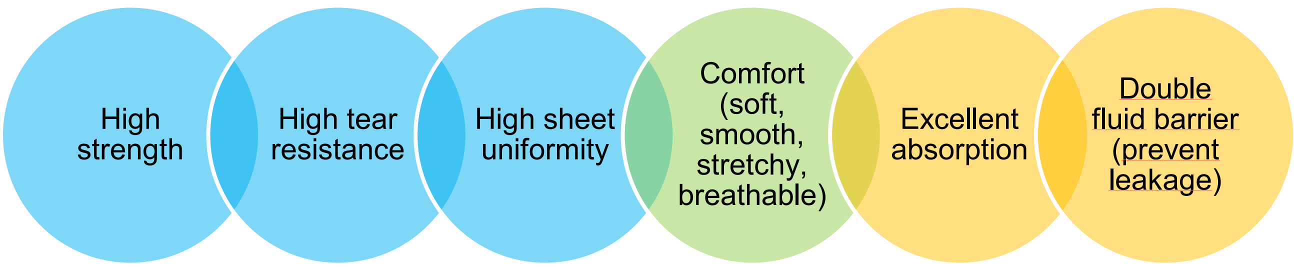


Figure 4. The most important requirements for hygiene nonwovens. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

[c] *Durable* nonwovens refer here to category; however, term durability also refers to a property of nonwovens

[d] The majority of SAP are made of sodium polyacrylate, a synthetic polymer

Table 16. Main web formation, bonding and finishing methods together with main raw materials for hygiene nonwovens.

Main manufacturing technologies	Main raw materials
• Air laying • Carding • Spunlaying • Chemical bonding • Thermal bonding (usually PE/PP bicomponent fibre) • Finishing	• Fluff pulp (absorption) • Cotton (softness, comfort, absorption, hypoallergenic) • Superabsorbent polymers (SAP, absorption) • PES, PE, PP (comfort, prevent leakage, strength, affordable) • Antibacterial Agents, softeners, other finishing

3.1.2 Medical

Nonwovens are widely used in the medical applications, especially to protect from infections and diseases, and contamination. In medical applications, the used nonwovens are in most cases single-use in order to avoid spreading of infections and contaminants. Applications in medical field are for example surgical; single-use caps, gowns, head covers, and face masks, and other applications; bed linen, lab coats, sterilization wraps, wound care, drug delivery, etc.

In medical nonwovens, there are specific requirements for the used materials and properties – the most important standards are ISO 13485:2016 which specifies requirements for medical devices and SFS-EN 13795-1:2019 which gives information on the characteristics of single-use and reusable surgical drapes, gowns and clean air suits used as medical devices.

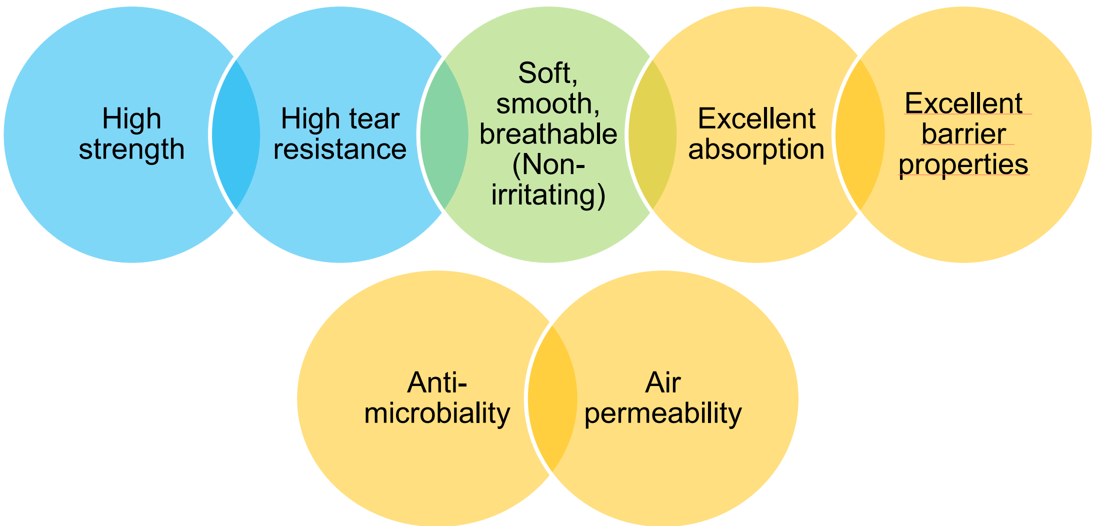


Figure 5. The most important requirements for medical nonwovens. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 17. Main web formation, bonding and finishing methods together with main raw materials for medical nonwovens.[19]

Main manufacturing technologies	Main raw materials
• Carding • Meltblowing • Spunlaying • Hydroentanglement (textile-like feel) • Needlepunching (various fibres, medium thickness) • Thermal bonding (synthetic fibres, SMS) • Chemical bonding (elasticity) • Finishing	• Polypropylene (PP; barrier properties, low cost, durability) • Polyester (PES; strength, sterilization) • Bi-component fibres (thermal bonding – added functionality) • Wood pulp (Absorbency, bulk, low cost) • Cotton (Absorbency, non-irritating) • Viscose (Absorbency, non-irritating) • Softeners, Antibacterial Agents, Water Repellents, Flame Retardant Finishes, Soil Release Agents

3.1.3 Wet wipes

Wet wipes are used mainly for cleaning and hygienic purposes, and they can be divided into two main categories; consumer wipes, which are further divided into personal care and household care, and professional wipes, which are used in industrial and medical applications. The consumption of wet wipes has increased enormously because of the convenience and easy use of the products, and also the use of disinfectant wipes has risen after COVID-19 started. Thus, the wet wipes can include added functionalities, such as antibacterial or disinfecting properties, making the products highly versatile for different applications. Applications of different wipes are listed below (Table 18):

Table 18. Classification of wipes based on application area. Modified from EDANA.[20]

Consumer wipes	Professional wipes
Personal care • Baby wipes • Cosmetic wipes • Intimate care wipes • Moist toilet tissue • Toddler training wipes	**Industrial applications** • Automotive • Electronic and computer industry • Food industry • Transportation • Printing
Household • APC (Hard surface cleaning) wipes • Disinfection wipes (Domestic use) • Floor wipes • Glass / Screen cleaning wipes	**Medical applications** • Hospital and community disinfectant wipes • Hospital grade disinfectant wipes • Patient care wipes

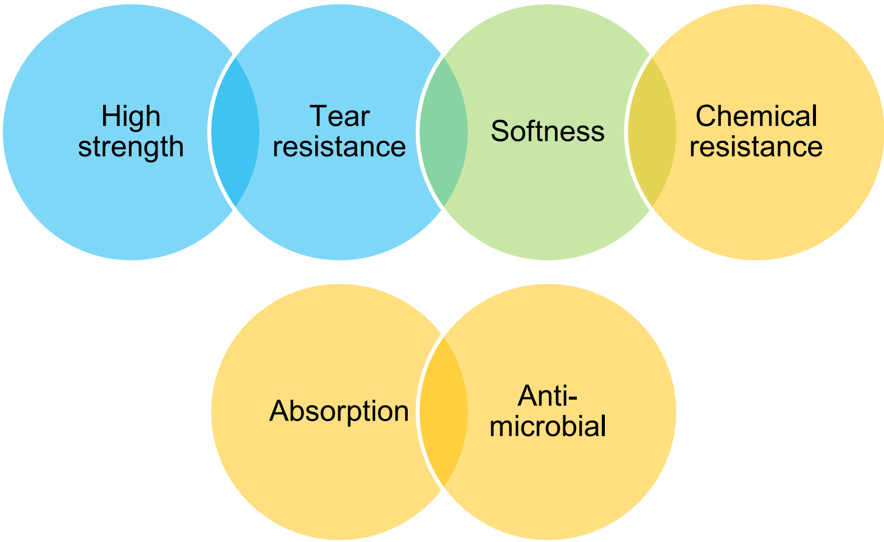


Figure 6. The most important requirements for wet wipes. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 19. Main web formation, bonding and finishing methods together with main raw materials for wet wipes.

Main manufacturing technologies	Main raw materials
• Air laying • Carding • Spunlaying • Meltblowing • Wet laying • Hydroentanglement • Finishing	• Polypropylene, Polyester (Strength, • Viscose (Absorbency, softness) • Wood pulp (Absorbency, softness) • Cotton (Absorbency, softness • Softeners, Surfactants, pH adjusters, Antibacterial Agents, Fragrances, etc.

3.2 Durable nonwovens

Most nonwovens are single-use and *disposable*, but *durable*, long-lasting nonwovens are also desired in a variety of applications, such as in automotive sector, geotextiles, and construction. *Durable* nonwovens can be classified into two different sectors – long-life and single-use or long-life and multi-use nonwovens. An example of a long-life and single-use nonwoven is some air filters that must be changed after some time, but the life of the product is at least months to over a year. An example of a multi-use, *durable* nonwoven is commercial wipes or launderable nonwovens (such as functional clothing), which can be used many times and in between the uses, they can be washed or cleaned without dramatic loss in their functionality or appearance.

3.2.1 Filtration

Nonwovens are used in many filtration applications to remove dust, aerosols, and organisms to provide cleaner air in different circumstances, such as clean rooms, hospital operating rooms, pharmaceutical and food industries. The filter products can be separated into three categories based on their filtration efficiency, i.e., efficient particulate air filter (EPA), high efficiency particulate air filter (HEPA), and ultra-low penetration air filter (ULPA).[21,22] For high-efficiency air filtration needing high specific surface area and porous structure, in which micro- and nanofibres are mostly preferred, electrospinning is a feasible manufacturing method.

The filtration industry is growing rapidly due to rising concerns about the human health and environmental responsibility. In automotive and energy sectors, requirements to decrease the air and water pollution to enhance protection of the environment are driving the development and usage of the filters. Since nonwoven materials can be versatile to be used in a variety of applications, they have an important role in decreasing the environmental pollution. Together with these sectors, also in high-tech industries, such as medicine, pharmaceutical and food industries, more efficient filters are needed in order to prevent spreading of finer micron-size particles. In filters, in which filtration of very fine particles are needed, meltblowing and electrospinning are commonly used manufacturing technologies to produce micro- and nanofibres.[21]

Table 20. Classification of filtration based on application area. Modified from EDANA.[23]

Air filtration	Liquid filtration
• HVAC – industrial heating, ventilation, and air conditioning • Consumer products (vacuum cleaner, cooker hoods, PCs, etc.) • Clean rooms	• Food and beverage (milk, wine, tea, etc.) • Pharmaceutical / Medical • Water • Blood • Hydraulic
Automotive filtration	**Specialty filtration**
• Engine air • Oil • Fuel • Cabin air	• Antimicrobial • Biopharmaceutical • Dust • Odour

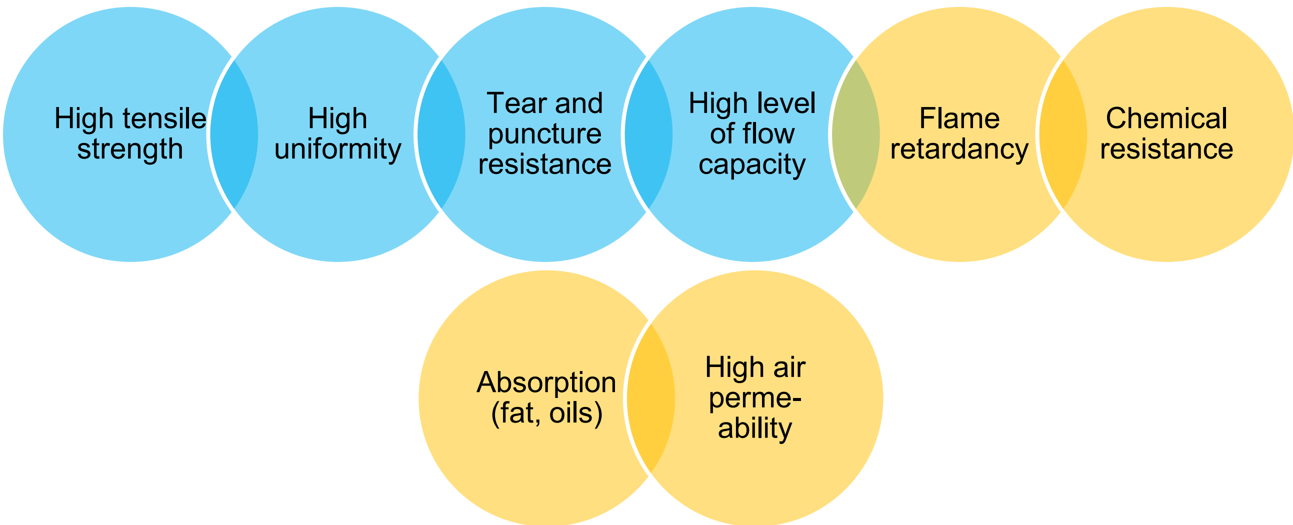


Figure 7. The most important requirements for filtration nonwovens. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 21. Main web formation, bonding and finishing methods together with main raw materials for filtration nonwovens.[22,24]

Main manufacturing technologies	Main raw materials
• Carding (Face masks, cooking oil filtration, etc.) • Air laying • Wetlaying (Coffee filters, HEPA filters, etc.) • Spunlaying (Air and liquid filtration) • Meltblowing (Fine filtration: dust, smoke, etc.) • Needlepunching • Hydroentanglement • Thermobonding • Finishing	• Most commonly polypropylene, polyester, polyethylene (e.g., SMS structure, strength and fine particle filtration, uniformity) • Natural fibres, e.g., cotton in some applications • Antibacterial agents, etc.

3.2.2 Household

Nonwovens are used in many household applications, including for example carpet underpaddings, abrasives, bed linen, curtains, floor covering, quilts and tablecloths. The reason why nonwovens are preferred over many other materials is for example the relatively low price, lightweight structure, and possibility to have different characteristics based on the application. The nonwovens used in household applications can also be created to contain antimicrobial properties in order to protect from for example dust mites in bedding. Other added functionalities or properties are for example anti-static, fire retardancy, and fluid resistance. The most used raw materials in nonwovens used for household applications are usually fossil-based PP, PA, or PET, but also recycled textile fibres (natural and synthetic), and cotton and viscose are used, depending on the needed characteristics for different applications.

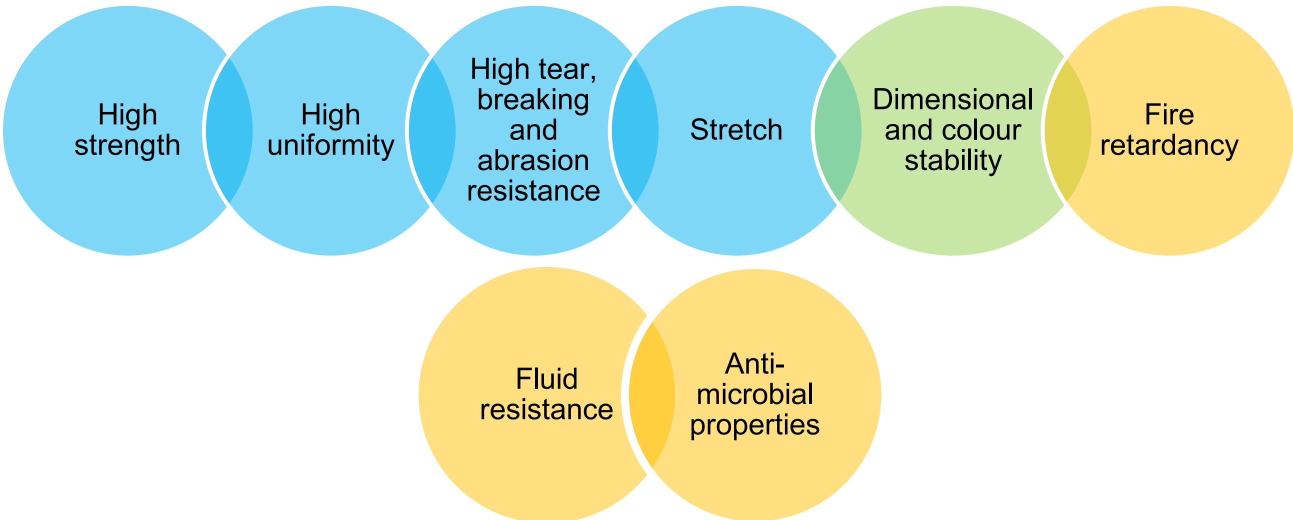


Figure 8. The most important requirements for household nonwovens. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 22. Main web formation, bonding and finishing methods together with main raw materials for household nonwovens.[25]

Main manufacturing technologies	Main raw materials
• Spunlaying • Wet laying	• PP, PA (Higher wear resistance) • PET (Greater softness than PP and PA, less wear resistance)
• Needlepunching • Hydroentanglement • Chemical bonding • Thermal bonding	• Recycled natural and synthetic fibres from e.g., waste textiles • Cotton • Viscose
• Finishing (Stain and flame resistance, antistatic properties, etc.)	• Fire retardant agents, antimicrobial agents, etc.

3.2.3 Agriculture

The agriculture sector utilizes nonwovens in a variety of applications for example to optimize the growth and quality of plants in gardens and greenhouses by for example optimized water and fertilizer absorption and distribution. The use of some nonwovens, crop covers, also protects the plants from harmful pesticides or changing weather, also resulting in lower amount of mechanical working. This all brings cost-effective benefits into the agriculture sector. Important characteristics for nonwovens used in agriculture are especially resistance to weather changes and protect from frost and heat. In many applications, the nonwovens used should have controllable moisture absorption and air permeability, together with protect from insects and allow gardening without use of high amounts of pesticides and herbicides. Depending on the application and desired lifetime, the materials used can vary. For longer-lasting, weather-resistant applications synthetic materials are widely used, mostly polypropylene and polyethylene for their long service life, water retention and low evaporation. For shorter-lasting products, natural fibres, such as cotton or wool, can be used to have biodegradable products.

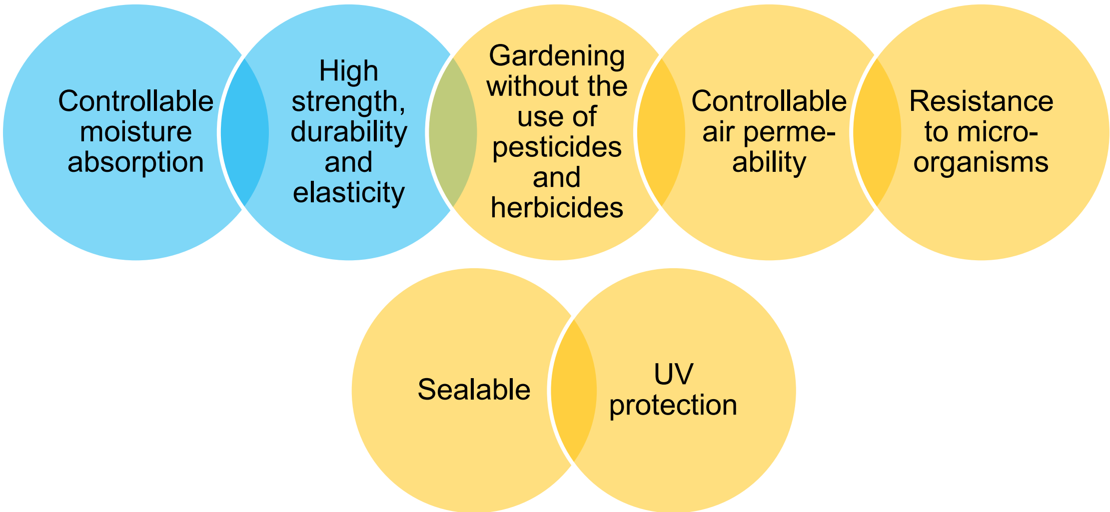


Figure 9. The most important requirements for nonwovens in agriculture. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 23. Main web formation, bonding and finishing methods together with main raw materials for nonwovens in agriculture.

Main manufacturing technologies	Main raw materials
• Spunlaying (mostly, for thermoformable materials) • Needlepunching • Hydroentanglement • Finishing	• Synthetics – e.g., PP, PE (Longer service life, water retain, lower evaporation) • Natural fibres – e.g., wool, jute, cotton (Biodegradation, low service life) • PLA (Compostable, long-term applications, e.g., row cover) • Antimicrobial agents, etc.

3.2.4 Geotextiles

In civil engineering, geotextiles are commonly used materials – nonwovens are used, for example, in railways, sport fields, motorways, and dams. Nonwovens are used mostly in applications in which reinforcement, filtration or separation is needed, but nonwovens can be used also for example in controlling erosion. The nonwovens used in geotextiles have to withstand fluctuations in temperatures, and have high strength, tear resistance, durability, and be lightweight. Geotextiles are usually made from synthetic fibres, mostly PP, but also PET and PE, due to their high strength, reinforcement, water control and erosion control properties. In some applications also recycled fibres are used, for example recycled polyester[26].

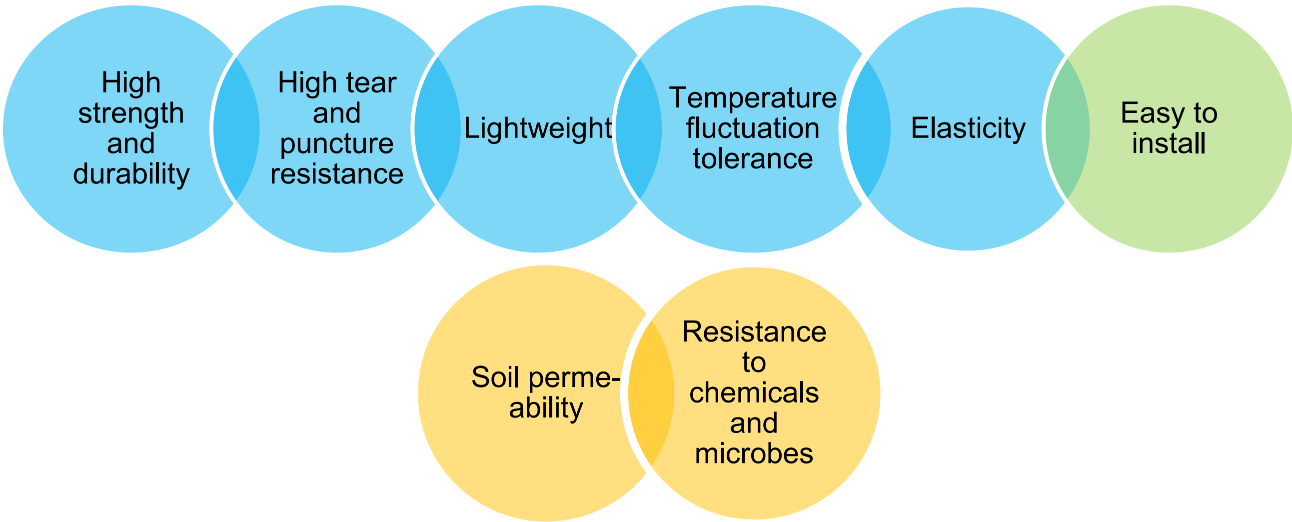


Figure 10. The most important requirements for nonwovens in geotextiles. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 24. Main web formation, bonding and finishing methods together with main raw materials for nonwovens in geotextiles.[27]

Main manufacturing technologies	Main raw materials
• Carding • Spunlaying • Mechanical (Needlepunching) • Chemical bonding • Thermal bonding • Finishing	• Mainly synthetic fibres (PP, PET, PE, PVC) • Natural fibres, e.g., jute, flax, hemp (Applications needing biodegradability) • Antioxidants, UV absorbers and stabilizers, flame retardants, antibacterial agents, etc.

3.2.5 Construction / Building

In construction or building sector, the nonwovens offer cost-effective and efficient solutions together with many added functionalities depending on the application, but thermal and noise insulation applications are common application areas in which nonwovens are used. Nonwovens used in construction are also in general easy to install with high durability offering a long lifetime, which saves money on a long run. The different application areas in buildings for nonwovens are, for example, thermal and noise insulation, roofing, air infiltration barriers, and flooring substrates. Because of construction materials are mostly designed to have a long lifetime, synthetic fibres are mostly used due to non-degradable characteristics to make sure they last for a long time. In addition, for example flame retardants are added in many cases in order to provide protection and fire retardancy.

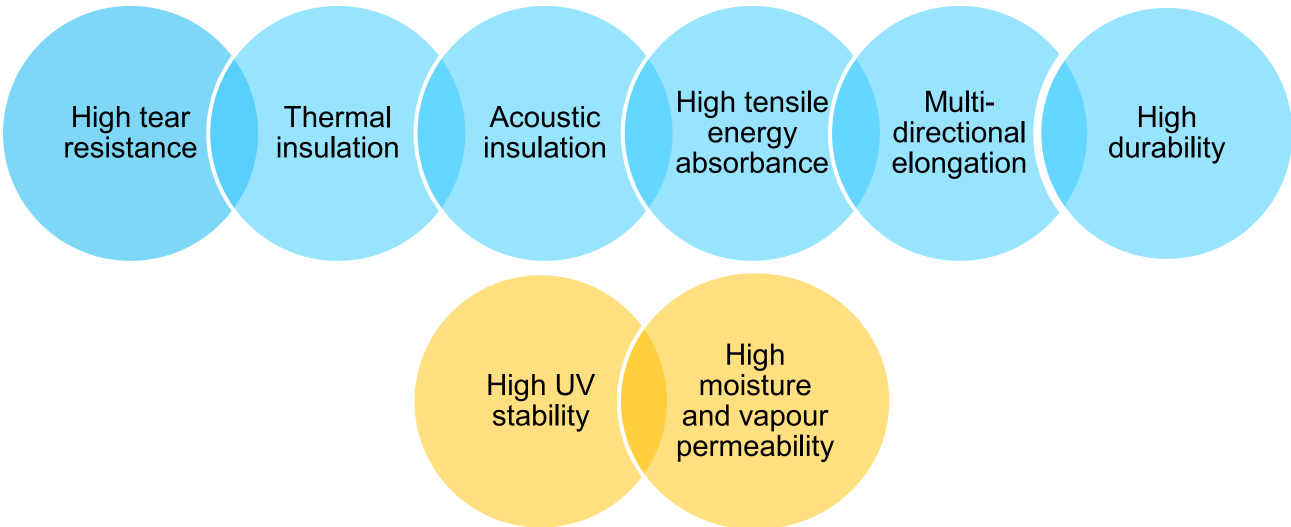


Figure 11. The most important requirements for nonwovens in construction sector. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 25. Main web formation, bonding and finishing methods together with main raw materials for nonwovens in construction sector.

Main manufacturing technologies	Main raw materials
• Carding • Spunlaying • Needlepunching (Most preferred in most construction and building applications) • Hydroentanglement • Thermobonding • Finishing	• Mainly synthetic fibres (PP, PET, PE, PVC) • Natural fibres, e.g., jute, flax, hemp (Applications needing biodegradability) • Antioxidants, UV absorbers and stabilizers, flame retardants, antibacterial agents, etc.

3.2.6

3.2.7 Automotive

Nonwovens can be found everywhere inside a vehicle, since nowadays over 40 automotive parts are made of nonwovens, and the amount is still increasing. Nonwovens are used from headliners and carpets and seats to air and fuel filtration, meaning the nonwovens are used in a wide range of different applications inside a vehicle. The use of nonwovens also not only offer improved safety (insulation, fire retardancy, resistance to extreme temperatures, moisture, fuels, and abrasion), comfort and performance, but also reduce weight of the vehicle resulting in lower fuel consumption, thus decreased greenhouse gas emissions.[23] The nonwovens contribute also to lengthening vehicles' lifetimes, thus making automotive sector more sustainable. One example of nonwovens lengthening the lifetime, is the tire reinforcements made of nonwovens[28]. They extend the lifetime of the tire, by providing durability and strength, but also better handling by sturdier structure[28].

In automotive applications, mostly synthetic fibres are used, PET and PP as a few of the most used ones, but also recycled fibres are commonly used, and also the use of natural fibres in automotive sector has increased.[29]

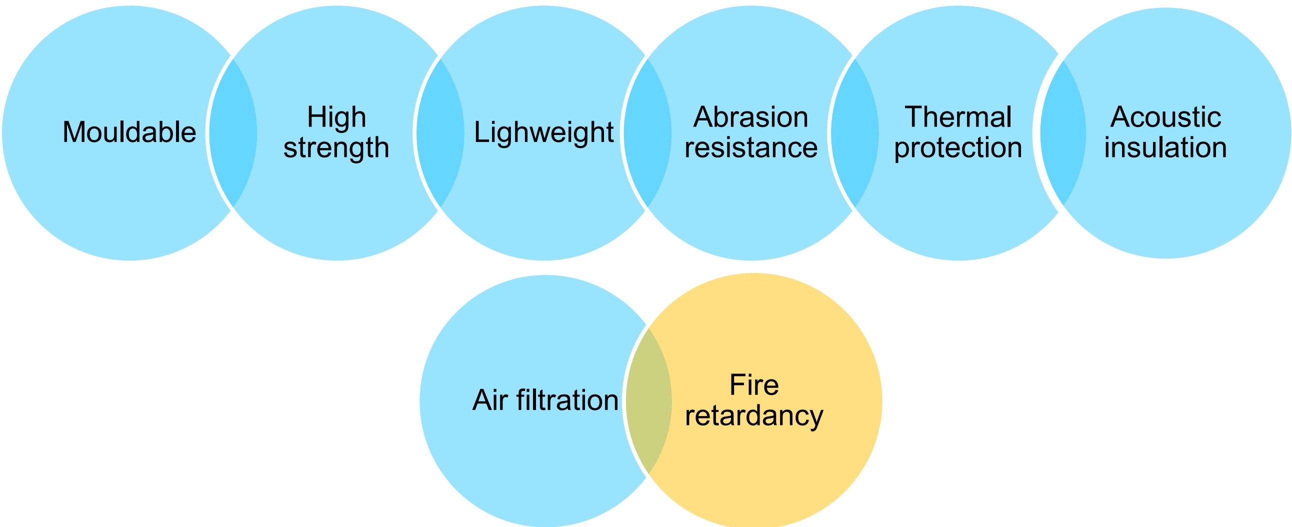


Figure 12. The most important requirements for nonwovens in automotive sector. The requirements are separated into three different categories – mechanical (blue), feel (green), and functional (yellow) properties.

Table 26. Main web formation, bonding and finishing methods together with main raw materials for nonwovens in automotive sector.

Main manufacturing technologies	Main raw materials
• Carding • Spunlaying • Meltblowing • Needlepunching • Hydroentanglement • Thermobonding • Finishing	• Synthetic fibres (PET, PP) • Natural fibres, e.g., cellulosic fibres • glass fibres • (Recycled) carbon fibres • Other recycled fibres • Flame retardants, etc.

3.2.8 Other

Nonwovens have been used for decades in clothing and footwear to achieve lightweight, strong, and malleable functions into different components, such as interlinings, in shoes, clothes and bags. Also, packaging is a field in which nonwovens are used in high amounts.

4. Sustainability drivers in the nonwoven sectors

4.1 Existing regulations and sustainability strategies

4.1.1 EU Directive on Single-Use Plastics (SUP Directive)

One of the most remarkable regulations regarding sustainable development inside the EU during the last years has been the EU's Single-Use Plastics Directive (SUP), which was approved in May 2019[30]. The directive bans certain disposable plastic products together with introduces restrictions on the use of plastics in certain single-use products, which impacts the selection of raw material in certain disposable product groups (Figure 13). In nonwoven sector, the SUP directive affects especially disposable hygiene products, such as wet wipes, diapers, and women's hygiene products.

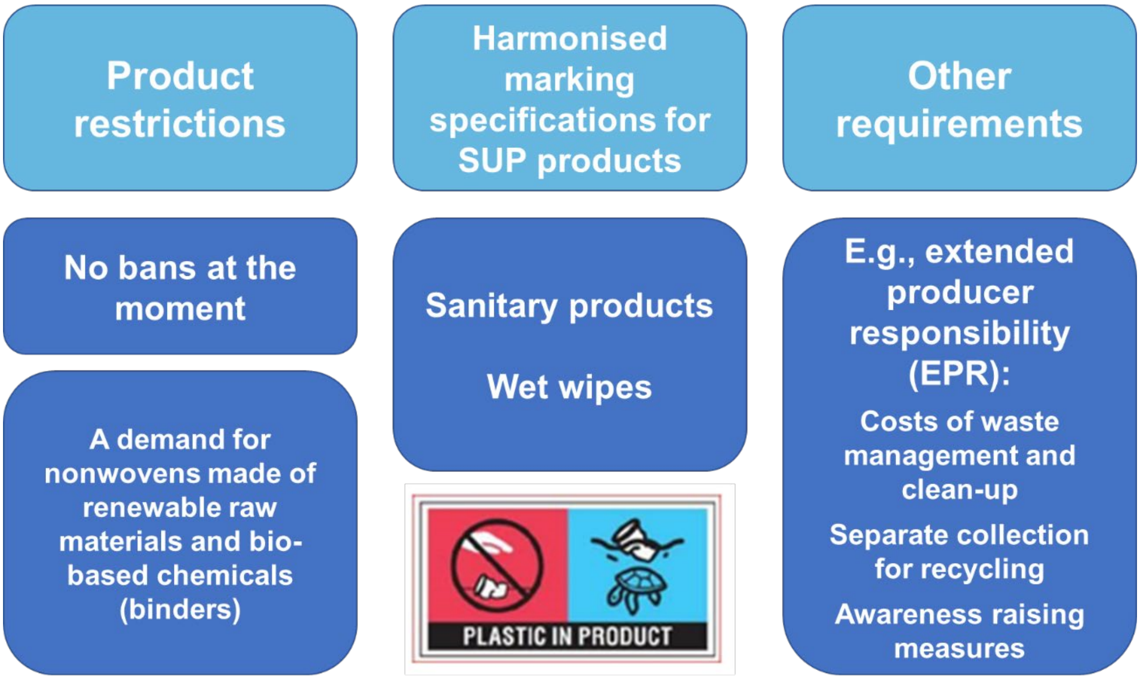


Figure 13. Product restrictions, harmonized marking specifications for SUP products, and other requirements, such as extended producer responsibility (EPR) as an example.

SUP directive has been criticized because of its broad definition of plastic:

> *"'plastic' means a material consisting of a polymer as defined in point 5 of Article 3 of Regulation (EC) No 1907/2006, to which additives or other substances may have been added, and which can function as a main structural component of final products, with the* ***exception of natural polymers that have not been chemically modified****"*

According to this definition, for example regenerated fibres (for example lyocell and viscose fibres) are not classified as 'plastic', thus these raw materials could still be used in disposable nonwovens. But for example, polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) are classified as 'plastics' according to this definition, as even though they are bio-based and biodegradable, they are classified as chemically modified polymers. PHAs have been a promising alternative to replace for example polypropylene in spunlaying process as they are compostable, recyclable, and biodegradable together with high functionality as in fossil-fuel based plastics, but according to SUP, they still would not be an acceptable choice in single-use products.

The SUP Directive has led to focusing on using more bio-based, biodegradable, and not chemically modified fibres, such as wood pulp, which is lower in cost, and organic cotton, which is relatively high in the price.

At the moment, latex-bonded nonwovens, or nonwovens treated with other fossil -based binders or adhesives, are excluded from SUP classification of products containing plastics. Although, it is good to keep in mind that this might change at some point as latex and many other binders used to bond the nonwoven webs are not biodegradable and classified as traditional plastics. Thus, in disposable nonwovens, the focus should not only be in more sustainable raw materials for fibrous web, but also in more sustainable, non-plastic binders and adhesives, such as CMC (carboxymethyl cellulose) and other bio-based binders have been and are being studied.[7]

4.1.2 Regulations on flushable wipes

There has been a gap in legislation on the flushability of disposable wipes, and this is why INDA and EDANA have created tests and methodologies to scientifically identify flushable wipes that would not cause harm to wastewater systems or the environment (Figure 14). They have published *Guidance Document for Flushable Nonwovens*[31], which has been adapted as the basis for flushability standards and regulations in many countries, such as Belgium and Spain. The problem arises especially with many disposable nonwovens, for example wet wipes, which many consumers might think are flushable even though they would not be flushable – majority of the wet wipes are not meant to be flushed. Many brands might also claim that their products are flushable, but still there is a risk of clogging the toilet and drains, if the products do not completely dissolve and start forming blockages in the sewer systems.

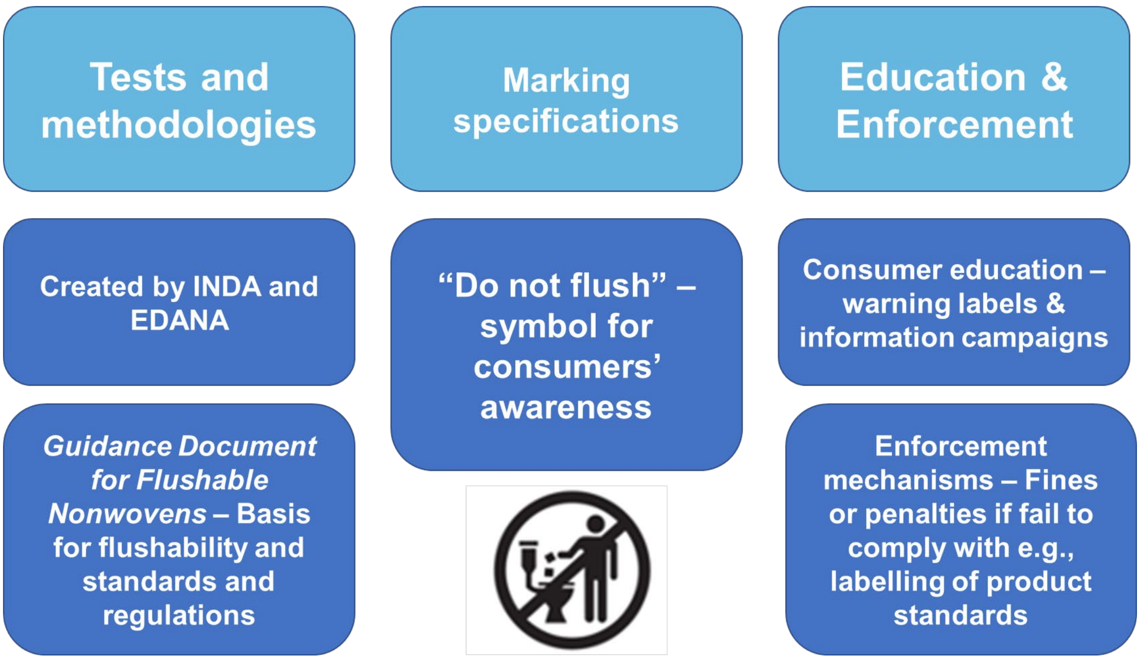


Figure 14. Different issues the Regulations on flushable wipes include – tests and methodologies, marking specifications and consumer education and enforcement mechanisms.

4.1.3 EU Strategy for Sustainable and Circular Textiles

The EU strategy for sustainable and circular textiles focuses on some textile products placed on the EU market, and the 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 utilization of recycled materials.[32] The framework and vision for the transition of the textiles sector is explained in the Strategy for Sustainable and Circular Textiles:

> *"**By 2030 textile products** placed on the EU market are **long-lived and recyclable**, to a great extend **made of recycled fibres, free of hazardous substances** and produced in respect of social rights and the environment. Consumers benefit longer from high quality affordable textiles, fast fashion is out of fashion, and economically profitable re-use and repair services are widely available. In a competitive, resilient and innovative textiles sector, **producers take responsibility for their products along the value chain**, including when they become waste. The circular textiles ecosystem is thriving, driven by sufficient capacities for innovative fibre-to-fibre recycling, while **the incineration and landfilling of textiles is reduced to the minimum**."*

Figure 15. Contents of the EU Strategy for Sustainable and Circular Textiles to make a transition to a more circular economy. This contains all stages of the products from designing to production, consumption, and waste management.

4.1.4 Sustainability in design – Verifications

There are specific certifications available which act as verifying proofs that the products that have launched in the market, can be considered as sustainable, and here are introduced three of them.

Cradle to Cradle (C2C)[33] is a product certification program, a system that examines the sustainability of the product in five performance categories (Table 27):

Table 27. Performance categories in Cradle to Cradle to examine sustainability of the product.

Performance category	Characteristics
Material Health	Ensure the materials used are safe for humans and the environment
Material Reutilisation	Enable circular economy already in product and process design Ensure all materials are in one of two circular cycles – technical and biological cycles
Renewable Energy	Ensure the quality of energy is green and from eligible renewable sources
Water Stewardship	Manage influent and effluent water streams responsibly Promote healthy watersheds and ecosystems
Social Fairness	Respect human right and contribute to an equitable society

ISO 14062 is an international environmental standard which integrates environmental aspects into product design and development.[34]

ISO 14001 is a standard which sets out the criteria for an environmental management system (EMS) and is the most widely used EMS in the world. This standard enables companies to certify their commitment to the environment.[35]

The EU Ecolabel is a voluntary certification to help the consumers to identify products and services which have lower environmental impacts compared to other products in the same field. The EU Ecolabel guarantees a more sustainable raw material production, a more environmentally friendly production process, restrictions on the use of hazardous chemicals and substances, and a more durable product.[36]

4.1.5 OECD Business Models for the Circular Economy

OECD (Organisation for Economic Co-operation and Development) has created five business models that support in transition to a more circular economy: circular supply, resource recovery, product life extension, sharing, and product service system (Table 28)[37]:

Table 28. OECD Business models for circular economy.

Model	Characteristics
Circular Supply	Replace traditional material inputs with renewable, bio-based, or recovered ones
Resource Recovery	Produce secondary raw materials from waste
Product Life Extension	Extend the use period of existing products
Sharing	Increase utilisation of existing products and assets
Product Service System	Provision of services rather than products – product ownership remains with supplier

Circular supply models aim to replace traditional material inputs, i.e., fossil-based materials, with bio-based, renewable, or recovered sources. This model focuses on creating closed-loop systems where resources and materials are reused, recycled, and remanufactured, and this business model can also be referred to as “cradle-to-cradle” product design model, as there is an intention to replace “cradle-to-grave” material flows with materials that can be manufactured into new products after their end-of-life.[37]

Resource recovery covers the production of secondary raw materials from waste streams. This includes collection of waste materials, sorting and separation of waste streams, and secondary production which involves the production of raw materials out of sorted waste materials. The uncertainty in this model is to ensure that the cost of this valorisation process would be small or less than the market price of finished materials. There can also be uncertainties coming from some sectors using the raw materials – for example in some sectors recovered materials are avoided because of high-performance characteristics, and for example in some nonwovens which demand high technical requirements, the use of recovered materials can be challenging. Also, utilizing this kind of a model also requires a high enough volume of waste materials and streams to be generated, and also the transportation costs along with other costs coming from the utilization process have to be considered in order to calculate if this kind of a process is economically feasible, especially if the produced material is of lower value compared to the virgin material.[37]

Product life extension aims to keep the existing products longer in the use, reducing the extraction of new materials and resources. The product life extension involves different models to extend product life[37]. *Classic long life* -model focuses on extension of product’s life through changes in product design – e.g., designing of more durable products. *Direct re-use* -model’s focus is on redistribution and re-use of products that otherwise would have discarded, and one example of this model is second-hand channels. *Maintenance and repair* -model includes extension of product life by fixing and replacing detective parts or components. *Refurbishment and remanufacturing* -model aims to give product a new life by restoring them to their original working condition.

Sharing models involve higher use of under-utilized consumer assets more, in most cases through lending or pooling. The sharing models have three key aspects: *Peer-to-peer or consumer-to-consumer (C2C) transactions, Temporary transfer of product ownership and more efficient use of under-utilized physical assets, rather than services provided by private individuals.*

Sharing models have two sub-types: *co-ownership and co-access*. The *co-ownership* includes the lending of physical goods, for example sharing of tools. This works well especially in urban, high population density areas, since this reduces transportation costs associated with changing the ownership of the product. The other sub-type, *co-access* includes possibility to take part in an activity that would have happened anyways.[37]

Product service system includes combining a product with a service part, and this system can be separated into three main models: product-oriented, user-oriented, and result-oriented product service system models. *Product-oriented* model focuses on the product, for example manufacturers can offer additional after-sales services as a part of buying the product. The after-sale service can be for example maintenance or repair offer as an extended product warranty or take-back agreement. *User-oriented* model focuses quite equally on both, products, and services. An example of this is for example office equipment leasing, or urban car sharing schemes, including customers paying for a temporary access to the product, and the service provider still has the full ownership of the product. This kind of a model provides access to the products just when the consumer needs it and pays for a product just for the period they need it, and this way higher costs of total ownership can be reduced, or also providing high quality products the consumers could not otherwise be able to afford. In *result-oriented* model, the services are promoted more than the product itself, and the specific outcome is more important than the means through which the outcome is achieved. A good example could be for example integrated pest management (IPM) in agricultural sector as a special form of chemical leasing. The company providing the service owns and handles the chemicals used for pest control and helps in optimal application of the chemicals to avoid crop loss.[37]

4.1.6 Waste hierarchy

In the EU waste policy, the goal is to improve waste management, promote waste collection and recycling, limit the use of landfills, and motivate consumers to change their habits to more sustainable way[38]. One of the key goals of the EU Waste Framework Directive is to *prevent* the generation of waste, and this is the most preferred option to be considered, after which *re-use* and *recycling* are the next preferred options (Figure 16). According to the EU Waste Directive, all EU member states are obligated to separately collect and recycle textiles in their end-of-life by the year 2025.

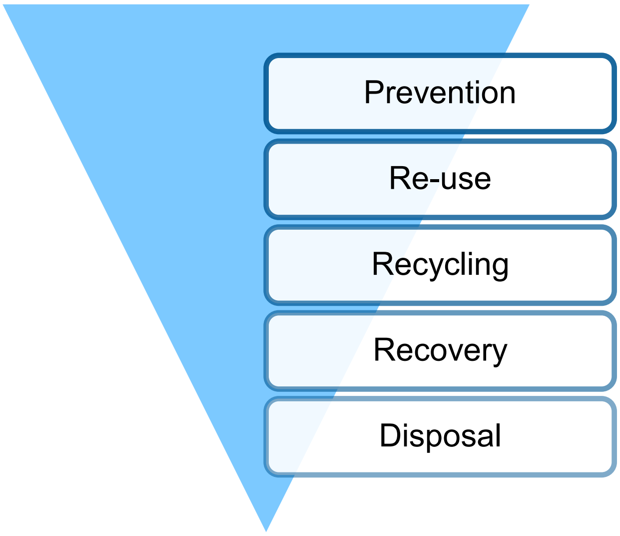
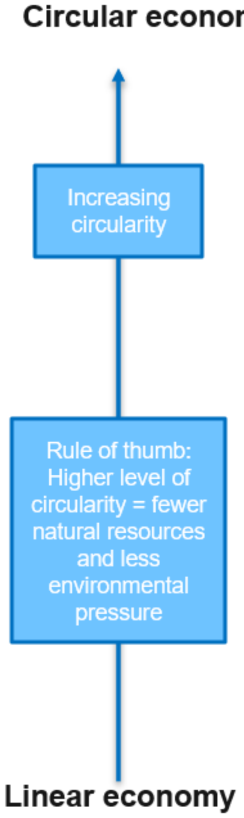


Figure 16. Waste Hierarchy based on the EU Waste Framework Directive from the most preferred option (prevention of waste) to least preferred option (disposal).

4.1.7 Nine R's

The nine R's of waste management shows nine solutions to manage waste from the most circular to linear solutions. In a higher circularity level, materials remain in the product chain for a longer period and can be repurposed or recycled after the product has been discarded, retaining the materials' original quality. This means lower use of new resources to produce new materials, since existing materials could be used. Although, it must be kept in mind that some circular solutions might increase the use of fossil fuels. As an example, if chemical recycling is wanted to be used to recycle the materials, especially highly contaminated ones, to their initial building blocks (polymers to monomers), this method usually requires high energy consumption, even higher than producing new materials, to synthesize the material. Still, in general, higher circularity level results in lower use of natural resources, and less environmental impacts.[39]

In the most optimal case, every choice would be as circular as possible, but in some cases that is not always possible, and other solutions must be considered. Figure 17 shows the 9 R's strategy, and the order from the most circular to linear solutions. Smart designing, manufacturing, and use (R0-R2) are the most circular options, and the next optimal options are related to extension of lifespan (R3-R7). The lowest circular level, meaning the lowest priority options, are related to recycling and incineration of the materials (R8-R9). Thus, the number indicates the circularity, the lowest number indicating the highest level of circularity.[39]



Smarter product use and manufacture	**R0 Refuse**	Make product redundant; abandon function or use other product
	R1 Rethink	Make product use more intensive; sharing or multi-functionality
	R2 Reduce	Consume less through efficient manufacture or use
Extend lifespan of product and its parts	**R3 Re-use**	Re-use of functioning discarded products by another user
	R4 Repair	Repair and maintenance of defects to keep original function
	R5 Refurbish	Restore and update
	R6 Remanufacture	Use parts in a new product with same function
	R7 Repurpose	Use products or parts in a new product with a different function
Useful application of materials	**R8 Recycle**	Process materials to obtain the same or lower quality
	R9 Recover	Incineration of materials with energy recovery

Figure 17. The Nine R's Strategy showing strategies from the most circular economy (R0 Refuse) to linear economy (R9 Recover – Incineration). Modified from[40].

4.1.8 Ted's Ten

TED (Textiles Environment Design) has developed a set of sustainable design strategies (Figure 18), which aim to help designers in textile and fashion industry to make more environmentally responsible choices in the design phase. The focus in these strategies is again more on fashion and clothing industry, but many of these strategies can also be applied to other areas, such as nonwovens.[41,42]

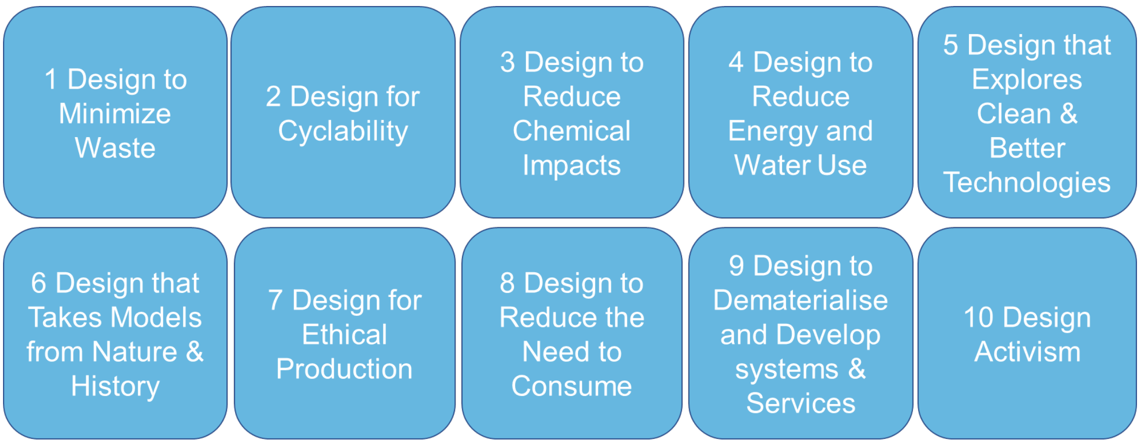


Figure 18. A set of sustainable design strategies developed by TED, Ted's Ten.[42]

The first strategy, *Design to Minimise Waste* introduces the idea to avoid producing products that are not going to be used, together with proper recycling after end-of-life of the product. This strategy aims to design "slow design" instead of fast fashion, and the focus in design should be on creating long-lasting, or durable, products. *Design for Cyclability* focuses on designing re-usable products or using of materials that can be recycled. *Design to Reduce Chemical Impacts* focuses especially on ecological material selection together with manufacturing processes to minimize environmental impacts. This strategy highlights the use of renewable, or bio-based materials together with technologies which do not require harsh chemicals in the process. *Design to Reduce Energy and Water Use* focuses on all phases of the life cycle, since especially in textile industry, high energy and water usage can occur at every stage of the lifecycle; production, consumption (consumers using and taking care of the textiles), and end-of-life (either disposal and/or re-use of the material). In the production phase, energy consumption and water usage are highly dependent on the manufacturing technologies that are used; thus, it is important try to find solutions that do not require high energy and water consumption. Already in design phase it has to be considered how the products will be used, and if/how they have to be taken care of, since for example in textiles technical coatings can reduce washing, and as a result decrease the water and energy consumption. The fifth strategy, *Design that Explores Clean / Better Technologies*, highlights taking care of the production stage so that the chosen manufacturing technique would reduce environmental impacts.

Design that Looks at Models from Nature & History means trying to find inspiration and solutions for future sustainable design straight from the nature, as in nature we can find many excellent solutions that have been developed under a long time. *Design for Ethical Production* considers ethical production, which values workers' rights together with sourcing of fair-trade raw materials. *Design to Reduce the Need to Consume* focuses on designing durable, long-lasting, "slow design" which the consumers really want and need rather than designing for example fast fashion, or seasonable, trendy pieces that will not last for a long time. *Design to Dematerialise and Develop Systems & Services* focuses more on the services and support rather than the products itself, for example leasing, sharing, or fixing or repairing the products. *Design Activism* encourages the designers to design and communicate the products beyond just the product itself to increase consumer awareness on the environmental and social impacts of the products they buy and consume. This can be seen in a form of, for example, publications, social media posts, blogs, or exhibitions that strongly take a stand on the problems of fast fashion or other issues in the industry.

4.1.9 Principles of Eco-Design

The Ecodesign Directive (2009/125/EC) set up a framework for mandatory requirements for more sustainable energy consumption in production of energy-using and energy-related products inside the EU[43]. The aim is to reduce the energy consumption, but the directive also considers more sustainable raw materials, water and chemicals consumption, green-house gases, and end-of-life (recyclability).

The proposal for a new Ecodesign directive, Ecodesign for Sustainable Products Regulation (ESPR), was published in March 2022, which is a more broadened approach to focus on more sustainable and circular products also in other areas than energy-using and energy-related products[44]. The aim of the directive is to ensure that the end-users have possibility to access to products that are energy efficient together with low environmental impacts. Ecodesign brings life cycle -thinking into the product design phase.

4.2 Aspects of sustainability along the whole life cycle

According to standard ISO 14006 (2020) – "Environmental management systems – Guidelines for incorporating ecodesign", life cycle thinking is important in sustainable business to focus more on circular rather than linear economy[45]. Life cycle thinking aims to take relevant environmental aspects into consideration in every step of the life cycle of the product. In this chapter, different environmental aspects are introduced along the whole life cycle of nonwovens in order to get more understanding on how more sustainable actions can be implemented in different stages of product's life cycle (Figure 19).

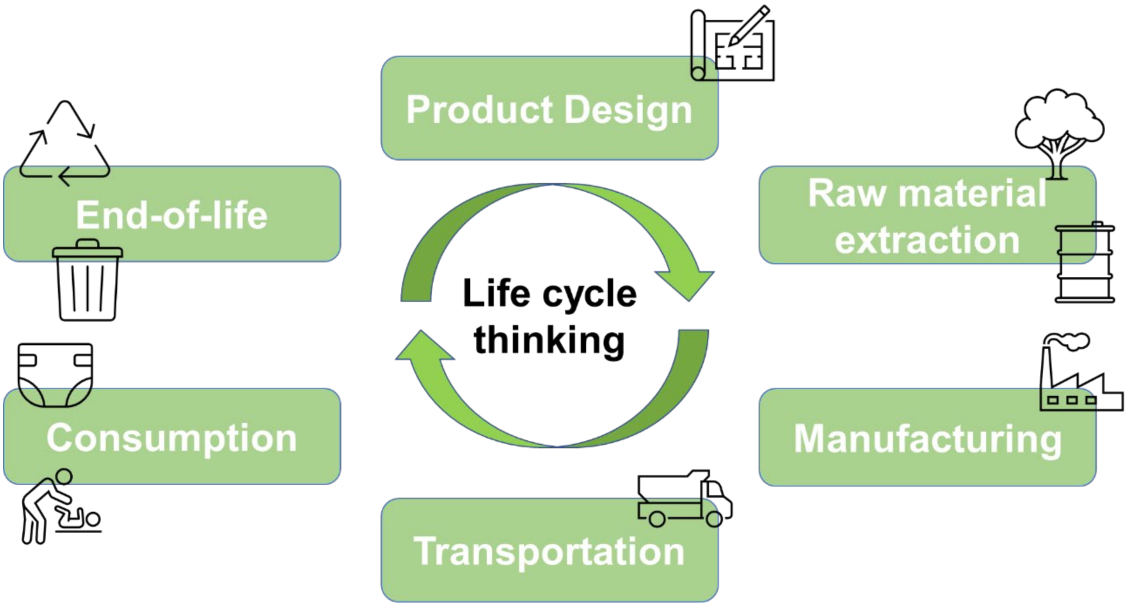


Figure 19. Steps of product's life cycle. In circular economy, every step of the life cycle are taken into consideration.[46]

4.2.1 Design

Designing products with sustainability in mind is crucial for reducing the environmental impacts of nonwovens. Designers should focus on creating products that are durable and require fewer materials, energy, and resources to produce. Use of biodegradable materials, reducing the number of layers of the nonwoven materials or decreasing the weight of the nonwovens in some other ways are a few ways to reduce the overall environmental impact, and these should be considered already in the design phase. Considering design strategies for sustainable and circular economy, design should take into account durability, reusability, repairability, ease of recyclability and use of recycled content, together with taking into consideration chemical aspects as well. Already in the design phase lightweighting should be considered, to test if the products could be created to be more lightweight, but still provide high performance.

4.2.2 Raw materials extraction

The selection of raw materials plays an important role in making nonwovens more sustainable. Using materials with less environmental impacts, such as biodegradable polymers, natural fibres, and recycled materials should be considered instead of non-renewable resources. Additionally, focusing on sourcing materials locally reduces transportation-related carbon emissions, and also sourcing from suppliers that prioritize sustainable practices, such as reducing water usage or using eco-friendly chemicals is worth to take into account. As already in the design phase, the lightweighting of the materials should be considered, and this can be done for example with finding new materials or material combinations to use fewer materials in the manufacture of the products. One aspect to consider also already in choosing of raw materials is to think about can the materials be recycled or re-used in the end of their lives.

4.2.3 Manufacturing

The manufacturing technologies of nonwovens should be designed to reduce energy and water consumption in the process. Modern manufacturing technologies can significantly reduce the environmental impacts of producing nonwovens. For example, efficient recycling of wastewater and using water-saving production methods can reduce water usage, using renewable energy sources can reduce carbon emissions, and efficient in-house recycling (e.g., recycling of material waste, energy, waste water in the process) reduces the amount of waste generated in the process.

4.2.4 Distribution

In distribution, more efficient and sustainable shipping and transportation processes include for example consolidation of shipments, use of fuel-efficient vehicles and biofuels, and reducing the distance that products need to be transported. As an example, it should be considered can some of the production steps be combined or made in the same place to reduce amounts of shipments and transportation. In addition, also packaging design is important part affecting distribution, as if the manufacturers reduce unnecessary packaging and thus lower the packaging weight, and design packaging in a way that it is optimized for efficient transportation and storage, savings in cost and environmental benefits can be achieved.

4.2.5 Consumption

Encouraging responsible consumption habits can significantly reduce the environmental impact of nonwovens, especially single-use nonwovens. This can be obtained by for example promoting more sustainable alternatives (bio-based, biodegradable, recyclable, reusable) to reduce the amount of fossil-based or single-use nonwovens consumed. In addition, for consumers should be provided clear instructions on how to take care of the products to prolong the lifetime and/or use times of the products, ensuring the service life is as long as possible.

4.2.6 End-of-life

Proper disposal of nonwovens, again especially single-use nonwovens, is critical to reduce their environmental impacts. Already in the designing phase the products should be designed in a way that they are easily recyclable or compostable, providing clear disposal instructions to consumers, and working with waste management companies to ensure that these products are properly disposed and do not end up in landfills or the environment.

Recycling can be inhibited by some factors[47]:

- *Consumers' awareness* – The right way of recycling must be clarified for consumers with e.g., proper, and **clear and simple** symbols and instructions in the product packaging.
- *Use of mixed fibres* – The more complex mix of materials have been utilized (e.g., natural fibres mixed with synthetic fibres and chemicals to bond the structure), the more difficult the recycling of materials is
- *Lack of information of the used materials* – If the recyclers do not know exactly the used materials in the product, finding the correct recycling technology to use becomes more challenging.
- *Chemicals used in the production* – e.g., use of flame-retardants, bonding agents, or anti-microbial finishes can be hard to remove in recycling, which consequently results in contamination of recycled fibres, and also can cause harm to the health of the people working in recycling facilities.

The nonwoven recycling concepts have been studied before at VTT[48], and it was found three concepts for the nonwoven industry that were determined to move towards more efficient nonwoven recycling. The concepts are:

1. **Use of recycled fibres** from mechanical, chemical, and thermal recycling processes or from other materials

2. **Use of novel nonwoven structures** aiming towards recyclability such as **monomaterial** approach as well as **novel and easy unravelling structures**
3. **Recycling of used nonwoven materials**

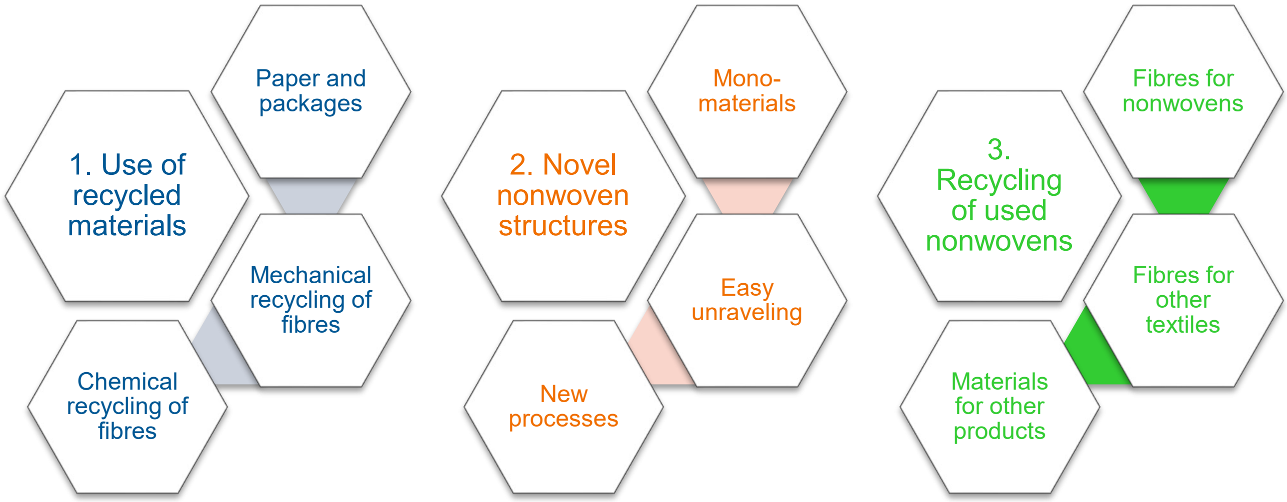


Figure 20. Three concepts for nonwoven industry to increase circularity.

In the use of recycled fibres, mainly two types of recycled fibres have been used so far in the nonwoven industry: thermally recycled PET (polyester) originating mainly from post-consumer PET bottles, and mechanically recycled textile fibres used for sound and thermal insulation applications which have mainly collected from postconsumer textile waste. In order to create more circular sector, other solutions have to be found, and in the concept of use of recycled materials, the idea is to increase the use of recycled fibres from for example paper and packaging, and from mechanical or chemical recycling.

By **novel nonwoven structures**, the recycling of nonwovens could be more efficient and easier. Most nonwovens are inexpensive single-use and disposable items, which usually consist of many materials and layers complicating the recycling of the products. Here, the mono-material approach could be one solution, if new ways are found to produce functional multilayer structures from one material, such as combining a porous inner layer sandwiched in between more dense layers around. In the structural approach, also easy unravelling, and new processes to produce nonwovens are important aspects to increase recycling of the materials.

The recycling of nonwovens has been focusing mainly on the recycling of in-house waste. If the used nonwovens are wanted to be recycled, the challenges are for example the hygienic issues of some of the used nonwovens, but also the lack of the collection system. Depending on the product and the fibres used, with proper recycling methods, the fibres could be again used to create new nonwovens and other textiles, or also get materials for other products. In addition to recycling, it would be beneficial for the industry to also focus on developing compostable nonwovens.

5. Sustainability strategies for nonwovens

5.1 Dimensions of nonwovens' sustainability

Nonwoven industry includes a wide range of different product segments, where different sustainability strategies may be needed to improve sustainability. In nonwoven industry, there is a high dependency on mass production of disposable and single-use products, such as baby diapers, wet wipes, and hygiene products, in which more important from the sustainability point of view is more the origin of the raw materials and the recyclability of the materials, whereas in more durable product segments, for example, automotive and construction, high durability of the materials is important, and also extension of lifetime, repairability and easy maintenance are important factors.

According to the existing circular economy and sustainability strategies together with needs and requirements in different nonwoven segments, different dimensions were created in which more *sustainable practices* in different nonwoven segments can be considered:

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

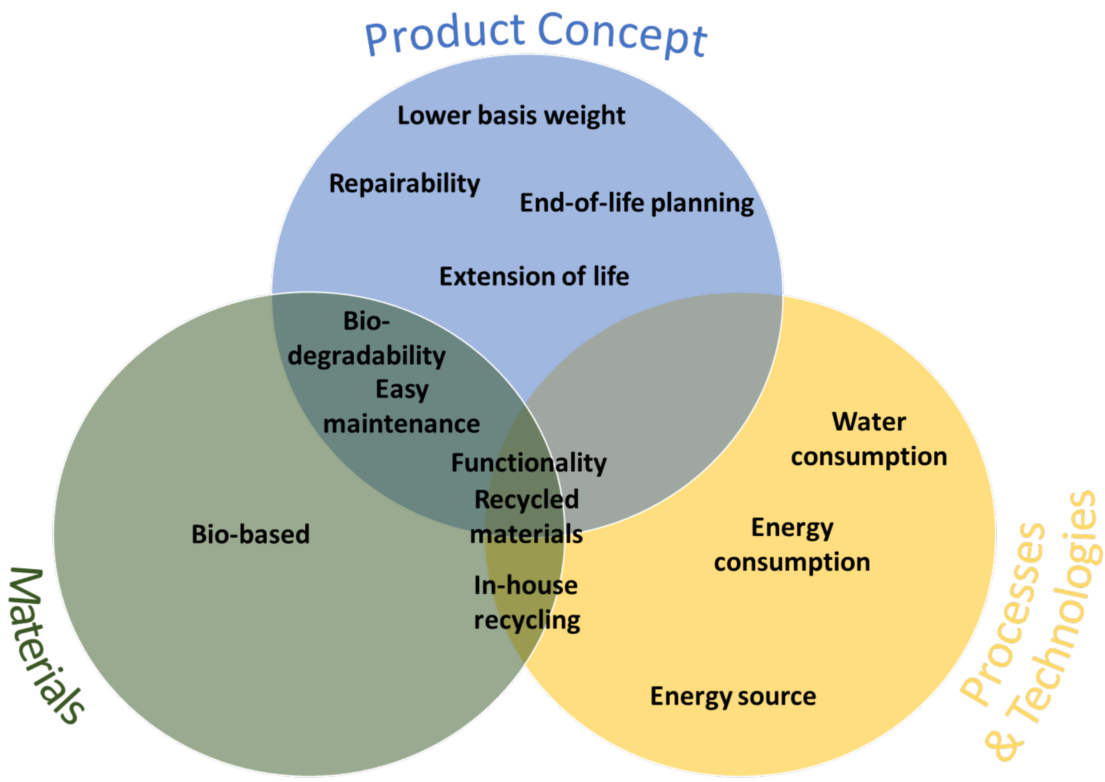


Figure 21. Dimensions to create more sustainable practices in nonwoven segments.

PRODUCT CONCEPT

In all segments, also according to existing circular economy and sustainability strategies, **prevention of waste** is the main target, and it highlights the importance of **circular product design** and **product concept**. The primary focus on designing products should always be in avoiding waste in every step of the product's life cycle – from choosing raw materials to end-of life of the products. This is also an approach that brings together all the designers, stakeholders in the supply chain, users of products, and waste management systems. Since the main target in circular economy is on reducing the extraction of natural resources and keeping the value of the products and services as high and long as possible, it is clear that waste prevention is the first strategy to focus on. For this reason, the target in **product concept** dimension is on the prevention of waste.

In strategies for waste prevention and management, the key waste prevention strategies were described, which included for example **design for durability**, **reuse of products and materials**, and **repair of the product** aiming to use less resources to create new products. These strategies are widely applied already in textile sector, especially to find solutions to growing fast-fashion clothing. As an example, clothing can be **repaired** or **re-sold** in second hand shops or flea markets, after which the products get a new life and are re-used, but in nonwoven sector it is not always that simple, as there are many products that must meet certain high criteria, and those might be not possible to be re-used or repaired if broken. Prevention of waste can be met with, for example, **use of recycled materials**, **lower basis weight**, focus on creating products with **high durability,** and properties preventing broken or faulty products, but also with **improving the used manufacturing technologies**. As an example, in manufacturing, especially in spunbond and meltblown processes, the edge trim and off-grade production usually are returned back into the extruder, which has been done mainly to reduce the cost, but this is also one way to prevent waste via **in-house recycling**[7].

Reduction of basis weight is one way to prevent excess waste, but also a way to reduce costs in the process[7]. In nonwoven products, a lot of costs come from the used raw materials. If the amount of used raw materials can be reduced with lighter basis weights, the costs can be lowered. Also, lower basis weights lead to lower transportation costs as the freight weights less, which results in smaller transportation energy use. The automotive sector is highly focused on lightweighting, as if components that are lighter in weight are used in the vehicles, it directly impacts the fuel consumption, and from that to CO_2 emissions[25].

One option to prevent generating waste is also **lengthening the product life** – **preparing for re-use**, **proper maintenance**, or **repair of the product**, which are also linked to prevention of waste. In nonwoven sector, there are many single-use products, such as personal care wipes, medical nonwovens, and absorbent hygiene products, where lengthening of product life is not feasible. Some other product segments, such as nonwovens used in automotive and construction industries, have longer life-span and high technical requirements meaning already in the design phase the **high durability** of the products is needed to be checked, and this way less waste is produced. In some single-use nonwovens, there could be a possibility to make a shift from single-use to multi-use nonwovens, and **product service system** could be utilized in this case meaning that a company would provide multi-use nonwovens as a service rather than a product.

After re-using, the focus in circular economy models is in **giving new life for materials**, i.e., **recycling** of materials, which is the last value cycle in the circular economy. Since circular business models aim to reduce waste being incinerated or ending up in the landfill, energy recovery and disposal are excluded from the models, even though some waste would be still generated, and not all waste could be avoided. Consumers also have an important role in this step, and proper guidelines and sharing clear information for consumers about proper recycling of the products in their end-of-life is important. This is a part of **end-of-life planning** which have to be thoroughly considered already in the design phase to create more circular rather than linear products.

Life cycle assessment (LCA) is an important tool already in the product designing and concept building phase to ensure that the new concept or changes made would actually be more environmentally friendly choice. LCA offers a comprehensive approach to evaluating the environmental impact of the products, assessing the entire lifecycle of the product from raw material extraction to manufacturing, transportation, use, and disposal. As an example, in the design phase, if the idea is to make a shift from disposable to re-usable product, it is important for designers to identify the environmental hotspots in the life cycle, and compare, which decision is a more sustainable option.

MATERIALS

Choosing of materials is part of the product concept, and it also determines possible processes and technologies. Thus, the choice of materials done in the design phase affects many properties and also lifetime and end-of-life possibilities of the products. In processes and technologies, there are limitations regarding the use of fibres and polymers, and for example used web formation method determines if recycled fibres can be used or not.

In materials choice, the main focus is on the **origin** and **end-of-life** of the materials as more sustainable materials are needed to reduce the need of virgin and fossil-based materials, but also the recycling options have to be considered. The novel **bio-based materials** should be studied more, and in addition, how **added functionalities** work with new materials and how different treatments affect the **biodegradability** or **recyclability** of the product. Depending on the segment, different kind of approaches are needed also in the choice of materials. As an example, in disposable single-use nonwovens, use of **recycled** or **bio-based** materials could be considered as one solution, but in some applications in which added functionalities or more durability is needed, the **durability** and **easy maintenance** should be prioritized, and as some applications require high level of purity and high technical properties, the materials have to be studied to meet the required criteria.

LCA tools are beneficial when deciding and selecting of materials with aim to create products with lower environmental footprints. By comparison of the impacts with LCA, informed decisions can be made on if the materials align with sustainability goals. In case of for example making a shift from fossil-based to bio-based binder for chemical binding of nonwoven web, it is important to clarify if the shift truly is more sustainable, as bio-based option does not always mean it is more sustainable than the fossil-based one. As an example, also the cultivation of the materials, water and energy consumption, and end-of-life options of the material or substance are important to check, together with also clarifying that the new material or substance meets the needed requirements or performance goals of the specific application or a product.

PROCESSES & TECHNOLOGIES

In processes and technologies, the needed changes to improve sustainability can be, for example, **greener energy sources**, **lowering the consumption** of **water** and **energy**, but also in the use of **chemicals**, especially considering if less or greener chemicals can be used still getting desirable output or properties. In this area, also **in-house-recycling** is important, but it overlaps with the used materials as the possibilities of in-house-recycling depends also on the used materials, fibres, and polymers. Depending on the nonwoven segment and desired properties, different raw material processing and web formation technologies can be decided, together with also bonding and finishing. Thus, the possibilities for more sustainable processes and technologies have to be considered case by case.

Analysing the manufacturing phase through **LCA** allows for the optimization of production processes, and also helps in identifying energy-intensive steps, and assessing resource consumption. As an example, by identifying the steps in which more energy-efficient methods could be used, and checking with LCA that the methods are more sustainable, this can lead to reduced energy use, which not only benefits the environment, but also can enhance cost-effectiveness of the process. In addition to more energy-efficient methods, in manufacturing phase also reduction of waste generation is important, and as mentioned before that in-house-recycling is also one way to reduce the waste generation, and the true impact of different ways of in-house-recycling can be also estimated with the LCA tools.

5.2 Product segment groups for sustainability strategies

The most common nonwoven segments were categorized based on the *lifetime* of the product to three different classes:

1) Single-use, short-term – Use time from minutes to hours
2) Multi-use and/or medium-term – Use time from days to months
3) Long-life, permanent – Use time over a year

The groups were also categorized based on the *complexity* of the processing, or *technical requirements* level, meaning that as an example, a product with higher technical requirements possibly has more functionalities compared to a product with lower technical requirements. The technical requirements level was separated into three levels: low/simple, medium, and high/complicated.

As a result, Figure 22 shows the positioning of different nonwoven product segments in relation to the *lifetime* and *technical requirements*. It can be seen that some of the product segments overlap different technical requirement levels and lifetimes, as segments contain different product types. Case studies which were chosen to be focused on for sustainability strategies in following chapters, are marked with orange squares. These case studies were chosen from different kind of segments in order to create sustainability strategies focusing on certain product groups with varying needs.

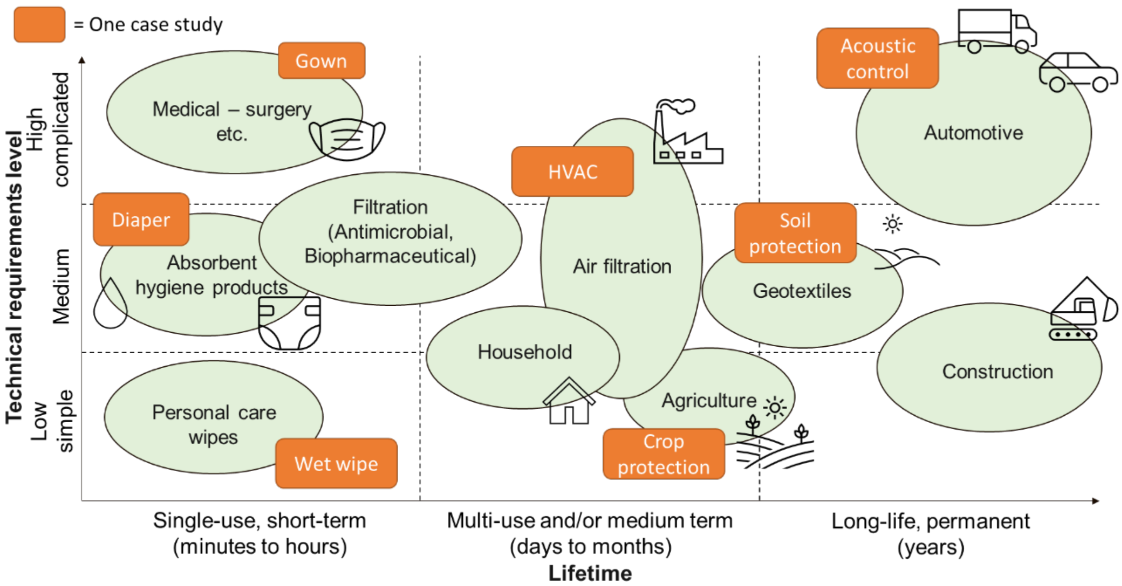


Figure 22. Positioning of common nonwoven product segments related to lifetime (single-use & short-term, multi-use & medium-term, long-life & permanent) and technical requirements level (low, medium high).

Different dimensions of sustainability (Figure 21) and lifetimes and technical requirements (Figure 22) were combined in order to create focus areas of sustainability for specific product segments. Figure 23 shows what kind of *sustainable practices* could be pursued in different *technical requirements levels*. In Figure 23, the different sustainable practises are classified based on the importance in different technical requirements level. As an example, products with lower technical requirements level, with less added functionalities for example, sustainable practices to be prioritized include lower basis weight (in *Product concept*), low chemical, energy, and water consumption (in *Processes*) and bio-based and recycled content (in *Materials*). Thus, these factors should be taken into account when planning more sustainable products with lower technical requirements level. It should be noted that many sustainability practises are important in many product areas, but the most important approaches for different product segments can be found with this kind of classification.

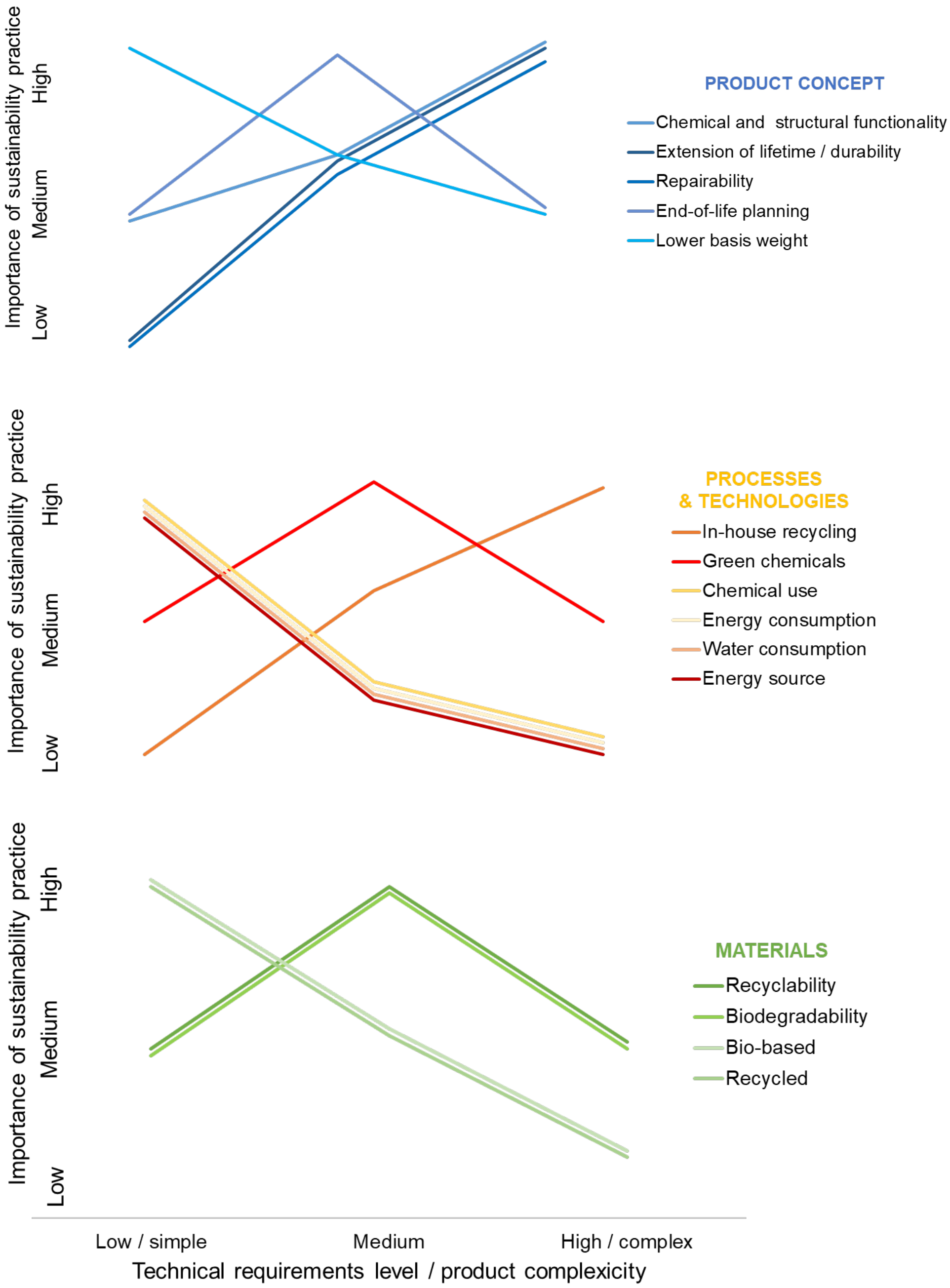


Figure 23. Simplified illustration of different sustainable practices categorized based on the importance in different technical requirements levels or product complexity. The categorization is made based on the available sustainability strategies and requirements in different products. Green lines represent actions inside materials dimension, blue lines represent actions inside product concept dimension, and yellow to red lines represent actions inside processes & technologies dimension.

The similar illustration was created for products with different lifetimes (Figure 24). Here, again, the importance of the sustainable practices is shown very roughly and as a general advice for the most important practises for products with different lifetimes. As an example, in single-use items, the end-of-life planning is very important, together with the origin of the raw materials. These products are usually mass-produced, resulting in a lot of waste after consumption, thus circularity of the products is also important. In more long-life and permanent products, high durability of the products should be prioritized as the products must have, for example, good mechanical properties or certain functionalities in order to meet certain lifetime of the product without damages or losing its properties before the desired lifetime. In addition, extension of product life has high importance as if the product can be longer without replacement, savings in costs and resources can be created.

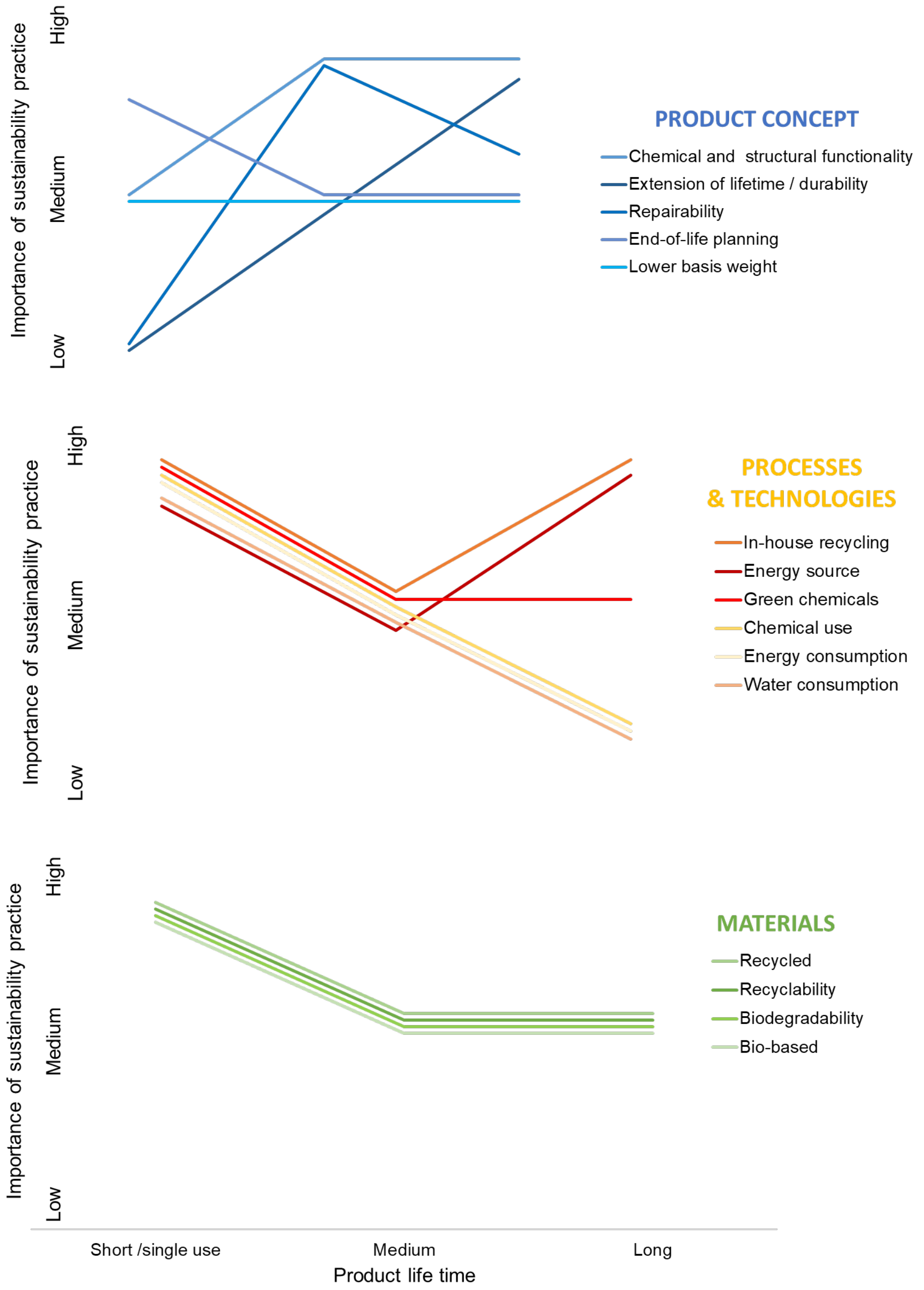


Figure 24. Simplified illustration of different sustainable practices categorized based on the importance in products with varying lifetimes or product life spans. The categorization is made based on the available sustainability strategies and requirements in different products. Green lines represent actions inside materials dimension, blue lines represent actions inside product concept dimension, and yellow to red lines represent actions inside processes & technologies dimension.

5.3 Disposable single-use products

In disposable single-use nonwovens, such as wet wipes, absorbent hygiene products and medical nonwovens, the environmental impacts can be significant as they are designed to be used once and discarded, mostly ending up in the landfill or incineration. Therefore, in disposable nonwovens, the importance of **material choices** together with **manufacturing and end-of-life choices** is high. Ideally, these nonwovens should be made from **renewable, recycled, biodegradable, or recyclable** materials in order to minimize their impact on the environment. This is a part of resource efficiency, which should be considered already in the design phase, as the production of disposable single-use nonwovens requires significant amounts of resources, also including considerations regarding energy and water in addition to raw materials. It is important to optimize resource efficiency throughout the whole lifetime of the products, from material sourcing to manufacturing, distribution, consumption, and end-of-life.

Since disposable nonwovens are used in large amounts because of the convenience and/or high performance or functionalities of the products, it is important to keep this in mind when trying to create more sustainable products, to create nonwovens that meet the requirements, such as **high durability** and **functionality**, together with being more environmentally responsible. As an example, if the functionality is the antimicrobial properties which have been traditionally achieved with using harmful chemicals in the structure, one possibility could be changing the type of the used chemical to still preserve the functionality of the material but making a shift towards more sustainable products.

Single-use nonwovens are mostly produced in mass production, and there, the **consumption of water and energy** in the process should be considered. Improving the **recycling of wastewater** and **in-house recycling** are a few means how to improve sustainability in the process, but also for example finding and trying **novel technologies** to produce the same products could be one feasible solution to produce more sustainable products.

Table 29. Importance of sustainable practices regarding materials, product design and processes and technologies in disposable single-use nonwoven products. Importance is expressed with stars (★), with an increasing number of stars showing higher importance for certain sustainable practice.

MATERIALS	IMPORTANCE	PRODUCT CONCEPT	IMPORTANCE	PROCESSES & TECHNOLOGIES	IMPORTANCE
Bio-based	★★★	Lower basis weight	★★	Water consumption	★★★
Recycled	★★★	Repairability	★	Energy consumption	★★★
Biodegradability	★★★	Extension of life	★	Energy source	★★
Recyclability	★★★	End-of-life planning	★★★	In-house recycling	★ –★★★*
Functionality	★ –★★★*			Green chemicals	★★★
Easy maintenance	★★				

** Depends on technical requirements level (low requirements – ★, high requirements – ★★★)*

5.3.1 Personal hygiene nonwovens – Wet wipes

Due to the convenience and easy use of disposable wipes, many consumers prefer the disposable wipes over re-usable and washable alternatives, and therefore, recyclability, compostability, or biodegradability, possibly flushability, together with the choice of more sustainable raw materials; recycled and/or renewable materials are important. If the raw materials are changed to renewable or recycled ones, one important question is, do the products perform well enough and have high mechanical strength while still being affordable and competitive compared with convenient products. In addition, consumers prefer easy usage of products together with easy disposal – and not all consumers are aware of appropriate disposal of the products, thus importance of clear end-of-life instructions of the products is high in disposable wet wipes.[49]

Single-use wipes need to have certain level of mechanical strength for the use phase, but in disposal phase, high mechanical strength can cause problems, since stronger wipes degrade slower in compost or in landfills. If the wet wipes have high dry strength, and they are composted or disposed into landfills, the degradation of wipes is lower. High wet strength of flushed wipes may cause blockages in the sewer systems as the fibre web in the wipes will remain strong without easily falling apart. As an example, some of the wet wipes that are labelled as flushable, can still contain some amounts of non-biodegradable or non-dispersible components to achieve good strength properties, resulting in wipes that pass flushability standard tests, but still are not completely dispersible[50]. The wet wipes should also have good absorption properties in order to absorb moisturizing liquid, but at the same time the wipe should be able to release the liquid in the use.[49]

Most single-use wet wipes consist of non-renewable thermoplastic fibres mainly because of good mechanical properties and low cost[49]. In addition, regenerated cellulose, namely viscose, is often used as a significant component or the only component in conventional wipes, as it provides enough strength to be used in wiping products. In addition, in wetting liquid, a long list of ingredients including, for example, softeners, antimicrobial agents, and fragrances can be used. Hydroentanglement is a commonly used method in binding of the fibrous network.

Depending on the planned end-of-life of the wet wipes, the amount and type of raw materials should be carefully decided in the design phase. As mentioned, sufficient dry and wet strength are needed in order to use the wipes properly without breakages, but the amount of strength needed depends on the end-of-life. High wet strength properties cause problems with flushable wipes, but if wipes are planned to be recyclable by chemical processes strength of the wipes is not an issue. In any type of wipes, using renewable raw materials could be prioritized, and especially as in the SUP Directive, wet wipes are in the list of objects that have or possibly will have restrictions or bans of plastics in the future[51]. Renewable raw materials suitable for wet wipes are, for example, regenerated cellulosic fibres, have sufficient absorbency and dry and wet strength properties, even though strength properties slightly vary between different kind of fibres [49,50]. The strength properties can be increased, for example, with higher fibrillation or using of novel regenerated cellulosic fibres. These cellulose-based fibres tend to have lower wet strength compared with synthetic fibres, but bio-based binders could be used as strength agents providing better strength properties while keeping the material base renewable.[49,50] If chemical binding is used, the binder should also be able to break down in the sewage systems in the case of flushable wipes.

Wet wipe production methods include wet laying, carding, and air laying for cellulose-based fibres and other staple fibres, and also direct-laid methods for thermoplastic polymers. If raw material base for wet wipes changes from fossil-based and non-renewable to cellulose-based or also recycled fibres, direct methods have to be replaced with processes suitable for staple fibres. As a bonding method with these, commonly used hydroentanglement works well in many cases, as it is rather sustainable method compared to, for example, chemical bonding which uses both, chemicals, and heat, to achieve consolidated fibrous network.

As new potential approaches, Zhang et al. (2018) studied wood pulp/Danufil nonwovens prepared by wetlaid/spunlaced method as a potential new dispersible wet wipes with excellent softness and smoothness.[52] Also, Mondi has developed a new carded-airlaid-carded (CAC) line, which can create a three-layer nonwoven for wipes, which could be used for hygiene and cleaning purposes[53]. Fully biodegradable 100% cellulose-based nonwoven can be made in the CAC line. This line uses fewer resources than comparable carded mono-structures, reducing the use of raw materials. When hydroembossing is added together with the CAC technology, softness can be increased.

5.3.2 Absorbent Hygiene Products (AHPs) – Diapers

The consumption of disposable absorbent hygiene products (AHPs) has risen enormously during the last decades, mainly because of convenient and easy use, high hygiene level, and skin protection. Particularly in developed countries, the easiness of the use of the products have been seen as an advantage. In European Union's Ecolabel criteria development, absorbent hygiene products have classified as one project under the revision of EU ecolabel criteria, aiming to promote the production and consumption of AHP's with a reduced environmental impact along the whole lifecycle of the products[54]. As in disposable wet wipes, also in AHPs, origin of the materials together with end-of-life planning are important aspects in making products more sustainable. However, as AHPs have higher technical requirements, the different functionalities and layers have to be considered carefully so that the various layers function as needed, together with still creating a product with circular end-of-life.

The most important technical requirements for AHPs include high strength together with tear resistance and high sheet uniformity. AHPs also include the highly absorptive layer and double fluid barrier to, for example, prevent leakage and absorb excess liquids. In addition, as AHPs are in contact with the skin, high comfort is one important property to create a soft, smooth, non-irritable and breathable product.

Absorbent hygiene products conventionally have different layers of different material for different functionalities. In diapers, for example, outer cover consists usually of polypropylene (PP), and elastic waistband of elastane. Impermeable barrier sheet to prevent leakage of fluids, is hydrophobic and usually consists of polyethylene (PE). Innermost layer is fluid transfer layer consisting of blend of thermoplastic fibres and at least 20% of hydrophilic fibres, to form material letting the fluid through, but still providing comfort and dryness. Beneath the fluid transfer layer is acquisition layer, which distributes liquid to the absorption core. Such absorption layer is common for all AHPs, and it mainly consists of super-absorbent polymers, and airlaid superabsorbent polymers (SAP) together with pulp is one option to use.[55]

SAPs is almost a necessity in AHPs in order to absorb high amounts of liquids in use. Although, it has been studied that SAPs would contribute to highest amount of environmental impacts of all components in AHPs and changing even a part of fossil-based SAPs to bio-based chemicals, environmental benefits were noticed[56]. Thus, shifting from fossil-based to bio-based SAPs is one solution. Some companies have already focused on replacing fossil-based SAP with bio-based one, and one example is Nippon Shokubai's Europe subsidiary, which in 2021 obtained an ISCC certification for their bio-based propylene, made from glycerol. Bio-based SAPs have been produced from other feedstocks as well, for example brown algae, bamboo, and wheat gluten protein. Also, chitosan and cellulose-based SAPs is one possible solution, and as an example, creating biobased SAP using cellulose to create a superabsorbent crosslinked hydrogel is one possibility.[56]

It should be kept in mind that biobased is not necessarily more sustainable than fossil-based material, and this has to be studied case by case. Mirabella et at.[57] studied the differences between PLA-based and fossil-based disposable diapers and found that the commercial fossil-based diaper had higher environmental impacts compared to the PLA-based diaper, although there is some risk of burden shifting. The results showed that PLA-based diapers had lower human toxicity, freshwater eutrophication and marine ecotoxicity, but the PLA-based diapers also had higher agricultural land occupation, land transformation and water depletion. Although, in this study, in PLA-based diapers, traditionally used SAP was reduced and replaced with chlorine-free pulp, which was found to be the highest contributor to total life cycle impacts. The reason for this was that chlorine-free pulp accounts for more than 50% of the total weight of the diaper. Thus, all the different layers have to be considered when making decisions in design phase of the products, and to make sure that the new bio-based product is actually better than the conventional product.

Mendoza et al. evaluated economic and environmental savings if the focus in disposable baby diapers was on eco-design and cleaner production rather than remodelling the disposable baby diapers to be multi-use products[58]. They studied the optimization of the absorbent core and bonding technologies. In this study, the used bonding technology did not include a gluing process nor latex, and these were replaced by a combination of thermo-mechanical and ultrasonic bonding processes. In addition, the absorbent core was optimized with decreasing the amount of fluff pulp and increasing the amount of superabsorbent polymer (SAP) by adjusting their ratio from 40/60 to 20/80 (w/w). They found that by these modifications, the costs could be reduced by 11% compared to a traditional product. They also found that these innovations reduce the environmental impacts by up to 67%.[58] Reifenhäuser Reicofil works also on new developments in new line generations to make reductions in the fabric weight while keeping the high properties[59]. They achieved to decrease the basis weight of a diaper top sheet from 22 to 12 g/m^2 without losing any quality properties. This reduction in basis weight does not just reduce the use of raw materials, but also affects CO_2 footprint of the end products.[59]

5.3.3 Medical nonwovens – Gowns

Medical nonwovens must meet specific safety and performance requirements to ensure they are suitable to be used in highly demanding healthcare environments. In medical nonwovens, as in other single-use and disposal nonwovens, the type of the raw materials is important in terms of sustainability. In addition, the end-of-life planning is in a high priority, thus, the aim should be on creating products that are recyclable or biodegradable. One solution is also to consider if single-use products could be changed to multi-use products. Also, in this case, for example, the antimicrobial properties or sterility of the products may be important depending on the product type.

Common requirements for medical nonwovens are high barrier properties, absorbency, biocompatibility, and antimicrobial properties, which have to be met, and here the durability and functionality are very important properties, which have to be considered when designing the products to be more sustainable. As an example, the choice of materials used in medical nonwovens is critical, as they must be safe and non-toxic, but also added functionalities like antimicrobiality may be needed.

In convenient products, both synthetic and natural fibres or polymers have been used as raw materials for medical nonwovens depending on the application. Synthetic fibres provide cost effectiveness, high performance (strength and durability), and also hydrophobicity to provide high barrier properties. PP is widely used, but also PE is used when, for example, easy sterilization is needed. Bi-component fibres can be used for thermal bonding and improving strength of material. In addition, natural materials, mainly wood pulp and cotton, can be used in order to achieve other types of properties. Wood pulp is used in applications desiring high absorbency, bulk and low cost, and cotton provides comfort, softness, and antimicrobial properties, and can be used for example, directly on wounds.

Synthetic materials are mostly prepared by meltblowing and spunbonding, and in their combination for SMS structures (spunbond-meltblown-spunbond). Carding is also a common method, especially when natural fibres are used, for example in combination with hydroentanglement. Also, needlepunching and chemical bonding are commonly used bonding methods. In addition, functionalizing agents are usually added into the structure, such as antibacterial agents, softeners, water repellents, and flame retardants.

One product example is medical protective clothing, mainly gowns, which protects from contamination and infections. Gowns made of nonwovens are disposable and they can be used alongside with reusable clothing. The criterion for reusable clothing is that it is required to be able to be washed at least 50 times, and these are sometimes made of nonwovens, but more typically of woven materials. Single-use nonwoven clothing is mostly preferred in situations where contamination risks can be high, and when the convenience of disposability is crucial, thus in healthcare environment this kind of properties are often necessary. Disposable protective clothing commonly offers better antimicrobial properties, which is why disposable protective clothing is mostly preferred choice when high hygiene levels are needed. However, single-use products generate higher amounts of waste. The reusable clothing can reduce waste generation when properly maintained, but they also wear out during washing, which also reduces the barrier performance. Reusable clothing is better suited in conditions which do not demand very high sterile conditions. In addition, the shipping and cleaning of the products, together with sterilization increases the environmental impacts. Thus, making a shift towards multi-use products should be considered case by case as both options can have their advantages and disadvantages in terms of sustainability.[60]

Both, disposable and reusable personal protective clothing are mostly manufactured via meltblowing or spunbonding from PP, PET, or PE, but development of materials using bio-based materials, such as PLA or cellulose, could be one option[61]. There are not that many studies about using bio-based materials in medical gowns, most probably because of the high hygiene standards and criteria for medical gowns, as many of the gowns are prepared by SMS method using mostly PP to create three-layer structure consisting of different characteristics: the spunbonded structure on the surfaces offer strength and wear resistance, while the meltblown layer in the middle reduces or blocks the penetration of for example bacteria and body fluids. One option to replace fossil-based material is to use biobased and recycled fibres. Heikkilä et al., for example, studied use of mechanically recycled cotton and cotton-polyester blend, pulp, regenerated cellulosic fibres and bi-component fibres for medical nonwovens. They demonstrated mostly biobased nonwovens materials with barrier layers added by lamination; however, areal weight of these materials was higher than synthetic references.[62]

Some studies have been made regarding the decisions on the raw materials and whether the medical gown should be disposable or multi-use product. As an example, in one study[63] comparative analysis was made between biodegradable gowns and their conventional counterparts, although 'biodegradable' in this study meant using polypropylene for both gowns, but for the 'biodegradable' gown, pro-oxidants were used to catalyze biodegradation. It was found that biodegradable gowns increased GHG emissions by over 10%, and a few other LCA calculations were worse. However, 'biodegradability' is something to consider in this study as the raw material was the same, fossil-based polymer. Not many reliable studies are found in which bio-based and biodegradable raw materials are used for medical gowns, possibly because of the use of bio-based materials as raw materials for medical gowns is still in its initial stage. More studies are focusing on the sustainability and performance of disposable and reusable medical gowns, and in terms of production costs, carbon footprint, and material waste, many studies highlight that reusable gowns are more sustainable[64–67]. It is worth noticing that most of the disposable medical gowns are nonwovens, whereas reusable medical gowns are still mostly woven nowadays. McQuerry et al.[67] studied the performance of disposable gowns (nonwovens) and compared those to reusable gowns (woven). They tested the performance of reusable gowns after 1, 25, 50, and 75 washes, and they found that even after 75 washes, laundering did not have a detrimental effect on the reusable gowns in any of the measured performance parameters. Although, disposable gowns have been found to be more comfortable during longer duration surgical settings[67–69] together with disposable gowns have in most cases higher barrier properties, i.e., prevents the transmission of bacteria, compared with reusable gowns which have been washed many times. Thus, depending on the situation, making reusable medical gowns can be a more sustainable way, but especially in case of longer duration surgical settings and situations needing high barrier properties, disposable gowns are still preferred. More research should be conducted in order to make disposable gowns more sustainable as well, for example with the use of more renewable raw materials.

5.4 Multi-use and/or medium-term products

In medium-term and/or multi-use nonwovens, such as many filtration products (air filtration, gas and fluid filtration), household nonwovens (bed linen, floor covering, abrasives), and agriculture nonwovens (plant protection, crop covers) one of the most important things to be considered in the design phase is to make sure the desired **performance** or functional structure of the product will remain its **desired lifetime**, and even better, if the product life can be extended with modifications in the structure already in the design phase, or making changes that makes the **maintenance of the product easier** for the consumers. In addition, **the education of the consumers** is important by for example making clear and simple instructions of the product so that the maintenance of the product is made easy and clear for the consumers.

Since the focus in multi-use products is more on the easy maintenance, functionality, and repairability of the products, the most important things to take into consideration in the design phase is to make sure the used resources (especially fibre raw materials and chemicals) result in **desired, or prolonged, lifetime**, without faults in the products, ruptures, or premature breakages because of structural properties, such as low mechanical properties decreasing the need of a replacement. However, still the type of the materials together with the end-of-life options is important here as well, and the focus should be also to improve sustainability by new bio-based or recycled options together with recyclable or biodegradable options as long as the functionality can be kept high together with long lifetime.

Even though multi-use or medium-term nonwovens are usually not produced in the same pace as single-use nonwovens, still the **consumption of water and energy** in production process are important as well. If the needed functionalities can be created with less or **greener chemicals**, together with more sustainable or energy-saving processes, more sustainable products could be created, but it always has to be tested, if the lifetime or use times can be kept the same, or even better if increased, with changes in production line or raw materials.

Table 30. Importance of sustainable practices regarding materials, product design and processes and technologies in multi-use and/or medium-term nonwoven products. Importance is expressed with stars (★), with an increasing number of stars showing higher importance for certain sustainable practice.

MATERIALS	IMPORTANCE	PRODUCT CONCEPT	IMPORTANCE	PROCESSES & TECHNOLOGIES	IMPORTANCE
Bio-based	★★	Lower basis weight	★★	Water consumption	★★
Recycled	★★	Repairability	★★★	Energy consumption	★★
Biodegradability	★★	Extension of life	★★	Energy source	★★
Recyclability	★★	End-of-life planning	★★	In-house recycling	★★
Functionality	★-★★★*			Green chemicals	★★
Easy maintenance	★★★				

** Depends on technical requirements level (low requirements – ★, high requirements – ★★★)*

5.4.1 Agriculture – Biodegradable crop protection

Nonwovens serve an essential role in modern agriculture practices, especially to enhance crop yields without utilization of harmful herbicides and pesticides. Most nonwovens in agriculture can be classified as medium-term products as they are usually changed in between different seasons, or also some of the nonwovens naturally biodegrade after some time. In this kind of medium-term nonwovens, the primary dimensions of sustainability to focus on are especially easy maintenance and repairability, but also the type of the materials together with end-of-life management are in rather high priority. Depending on the desired application and lifetime, the nonwovens should be made from recycled and recyclable materials or bio-based and biodegradable materials.

For nonwovens used in agrotextiles, high performance is also a key factor to consider, as the products are used even in extreme climate conditions, thus they require sufficient tensile strength characteristics without significant deterioration, controllable moisture absorption and air permeability, together with resistance to micro-organisms.[70]

Traditionally, straw, glass, and plastic films have been used to protect crops from temperature fluctuations, and also lightweight cotton fabrics have been used especially on freshly planted seeds to not be flushed away from their place. First nonwovens to replace these films and textiles to cover plants were created from polypropylene via spunbonding method and is still commonly used in many agricultural nonwovens. Additionally, nonwovens made of natural fibres, such as wool, jute, and cotton have been used in applications demanding biodegradability. Thus, the use of raw materials in crop covers depends due to some extend on the end-use and the desired lifetime of the products.[70]

If the aim is to produce nonwovens for agricultural applications which should biodegrade in the end of its life, natural, biodegradable fibres, for example, cellulose-based fibres, should be considered as they biodegrade naturally. These kinds of raw materials could be used in short-term applications, as in longer-term applications the desired service life could be shortened due to premature deterioration of the raw materials. If longer life is needed, natural thermoformable polymers, such as PLA and PHAs could be considered as binders to strengthen the material together with lengthen the lifetime. PLA and PHAs could be also used to replace some of the synthetic fibres (PP and PE mostly), and as most agricultural nonwovens, such as crop covers, made from synthetic fibres are manufactured via spunbond method, the same manufacturing method without remarkable modifications could be used for PLA and PHAs.[70]

In one study by Di Mola et al.[71], a traditional LDPE film used for mulching was compared with biodegradable starch-based film which was treated with a natural stabilizer. They studied the conditions and quality of the soil and did not study long-time effects or performance of the films, but their results show environmental benefits (i.e., more sustainable choice) when using biodegradable film as a replacement for traditional film. In addition, one interesting study by Chen et al.[72] showed that on average, consumers are willing to pay over 10% more for strawberries grown on biodegradable mulch compared to traditional fossil-based mulches. Regarding these findings, increasing the use of biodegradable nonwovens in agriculture leads to a reduction in the use of traditional fossil-based plastics. However, in some studies[73,74], it has been discussed that even though biodegradable mulches offer environmental benefits, the long-term impacts of biodegradable mulches on soil health and specialty crop productivity have to be studied more, especially the question of release of micro- and nanoparticles and their effects on soil ecosystems and crop quality. Thus, use of biodegradable raw materials for agricultural nonwovens, focusing on mulches, looks promising, but further studies are still needed for longer-lasting effects of the use of biodegradable materials.

5.4.2 Air filtration – HVAC

Importance of air quality has risen lately because of concern of effects of lower air quality (e.g., different microparticles) on human health, which has led to more in-depth investigation of regulations and requirements on air filtration systems. Comparing indoor and outdoor, indoor pollutant levels are commonly higher (from 2 to 100 times), and as indoor air pollutants are included in the top five environmental risks to public health, importance of efficient filtration systems is highly needed[75]. Thus, in air filters, the high performance is important to capture tiny particles and improve human health. In addition, in air filtration, the optimization of the air filtration system is important as, for example, some filters can result in higher resistance to airflow which increases the energy consumption as the motor of the system must work harder for efficient air flow. If the resistance to airflow can be reduced via, for example, changing the design of the filter, this results in lowered energy consumption.[76]

The filtration efficiency can be determined with MERV rating, standing for minimum efficiency rating value. The rating range of MERV measurement system is from 1 to 20, 1 meaning the lowest and 20 the highest filtration efficiency. The lowest MERV rates can block only the largest particles, mostly over 10 microns in size, and this kind of filters can be for example in filters used in windows' air condition units. The higher the MERV rate is, the smaller particles can be captured, and over MERV 13 rated filters are mostly used to filter out bacteria and viruses, so mostly found in pharmacy and hospital applications, and over 16 MERV is also called as HEPA (High efficiency particulate air filter).[77,78]

Important mechanical properties for air filters include high tensile strength, uniformity, high level of flow capacity and tear and puncture resistance. In addition to capability of capturing tiny respirable particles, such as dust, and micro-organisms, some other important added functionalities are for example anti-microbial, anti-static, and flame retardancy, thus the importance of performance is high[75]. In addition, easy maintenance of the filters is an important aspect to focus on to make cleaning and maintenance of the filter easy for the users, possibly prolonging the lifetime of the filter.

Because of considerations regarding sustainability, the source of the materials together with end-of-life management are important in order to make more sustainable filtration media. Indoor air filtration systems (HVAC systems) commonly include spunbond and meltblown nonwoven fabrics made from synthetic thermoformable fibres, mainly PP and PE[75]. Some of the air filters used in HVAC systems are also made of recycled materials, for example from recycled bottles[79,80]. Even though most of the filters used are still disposable, reusable and washable filters are available[80], although, these filters are also mostly still made from fossil-based plastics, and use of bio-based raw materials in air filters is still in its initial stage.

In one study by Schippers et al.[81] they studied the potential of using PLA as bio-based media for nonwovens used in air filtration. They used meltblowing to create PLA monofilaments and tested environmental aging in high temperature and fluctuating relative humidity (RH) to see material degradation under conditions related to air filtration application. The results showed good stability and confirmed that PLA is a potential bio-based media to be used in air filtration applications. Also, in one review by Souzandeh et al. (2019)[82] they reviewed the potential of a variety of biopolymer-based filtration materials and found that especially with a combination of functional polymers together with electrospun nanofibres could be an effective strategy to prepare especially high-performance air filters, but they also stated that the research in the field of natural polymer-based air filtering materials is still in its initial stage. Although, they stated that the development of air filters is calling for the knowledge and new technologies including incorporation of biomaterials. Based on these findings, modification or improvement of manufacturing methods for bio-based materials for air filtration applications is still needed, but good improvement has been done already.

5.5 Long-life and permanent products

Long-life and permanent nonwoven products need to last for over a year to many years. These products include for example construction materials, such as thermal and noise insulation, roofing and flooring substrates, and materials used by automotive sector, such as carpets and flooring, airbags, boot liners, and boot carpets. One of the most important characteristics of these applications is the **high durability** of the products, so that the nonwovens last in certain climate or environmental conditions without losing their performance or mechanical properties. In this case, the **end-of-life planning** of the materials is important especially in the higher technical requirements -products, as in these products the materials used can be of higher quality and could be recycled and used as secondary raw material for new products. In addition, regulations for **recycled content** are under target, for example, in automotive sector as European Commission has proposed a regulation in which the aim is that at least 25% of the plastic used for building a new vehicle, is required to be recycled materials.

Since long-life products usually must have high performance and many functionalities, energy and water consumption together with other resources in the production cannot always be decreased in order to keep the high-performance level of the products. Here the **in-house-recycling** is important meaning, for example, the reduction of fibre waste and better circulation of wastewater. Furthermore, greener energy sources can be used in the production in order to make more sustainable shifts in the production process. Also, the **investigation of using of new materials and technologies** is one solution to decrease the environmental impact of the products. As an example, in the geotextiles industry, some nonwoven innovations have led to the replacement of gravel that is used in road construction, which results in **lowering the weight and amount of the materials** while still offering the desired functionalities and product performance[59].

Table 31. Importance of sustainable practices regarding materials, product design and processes and technologies in long-life and permanent nonwoven products. Importance is expressed with stars (★), with an increasing number of stars showing higher importance for certain sustainable practice.

MATERIALS	IMPORTANCE	PRODUCT CONCEPT	IMPORTANCE	PROCESSES & TECHNOLOGIES	IMPORTANCE
Bio-based	★★	Lower basis weight	★-★★★*	Water consumption	★
Recycled	★-★★★*	Repairability	★	Energy consumption	★
Biodegradability	★★	Extension of life	★★★	Energy source	★★★
Recyclability	★-★★★*	End-of-life planning	★★★	In-house recycling	★★★
Functionality	★★			Green chemicals	★★
Easy maintenance	★★				

** Depends on technical requirements level (low requirements – ★, high requirements – ★★★)*

5.5.1 Automotive – Acoustic control

Nonwovens cover approximately 10% of the interior textiles in vehicles[83]. They contribute to improved safety (e.g., fire retardancy, resistance to extreme temperatures, moisture control), insulation, and comfort. As mentioned previously, in automotive industry upcoming regulations and already pushing demands of more sustainable industry, recyclability and using recycled materials for new vehicles is in high importance. Thus, in automotive industry the source of raw materials together with end-of-life planning are of high importance.

One important component in automotive industry is acoustic control for noise and vibration reduction. The nonwovens used in acoustic control must have several characteristics to be designed for sound absorption. The nonwovens created for acoustic control must be designed to dampen sound vibrations and improve the overall acoustic performance of the vehicles' interior parts. The materials must have high porosity in order to allow sound waves to dissipate energy within the nonwoven structure, resulting in reduction in noise. The materials also have to be lightweight as in automotive sector the weight reduction is important, which is essential for fuel efficiency, environmental impacts, and overall performance of the vehicle. The materials should be flexible for easy install in different parts inside the vehicle, including trunk space, headliners, and door panels. In addition, the materials should be designed to be durable and long-lasting so that they do not need to be changed or replaced often, designed to withstand humidity and temperature fluctuations, and maintain sound-dampening properties over a long time.

Conventionally, synthetic fibres, mostly PP and PES, have been commonly used for acoustic control in vehicles. To make more sustainable choices, for example, reducing weight of the vehicle is one opportunity to cut the materials together with emissions, and making a change towards bio-based materials is one good solutions. Natural fibres have been recently tested more to be used in nonwovens for automotive industry, and one example is combination of flax together with PP prepared by carding and hydroentanglement, and still bonded by thermal bonding[84], but same kind of combination have been also prepared by needlepunching to form more dense nonwoven mats[85]. The prepared material showed good characteristics to be used as acoustic control materials. Peforetti et al.[86] studied the use of recycled cotton in acoustic components in vehicles and made a comparative LCA case study between polyurethane-based and recycled cotton-based materials. It was found that the recycled cotton was more environmentally friendly alternative compared to polyurethane-based option. One of the main reasons was the lower weight of recycled cotton -based alternative, thus besides focusing on the origin of the materials, also the weight of the final product is in high focus when creating more sustainable materials for nonwovens in automotive industry.

5.5.2 Geotextiles – Soil protection

Nonwovens are used in a variety of geotextiles. The main functions of nonwovens used in geotextiles include for example filtration, drainage, separation, reinforcement and protection[87]. As in automotive industry, also in geotextiles the source of raw materials together with end-of-life planning are highly important to create more sustainable products. Opting for recycled materials can help decrease waste and reduce the demand for new resources, but as the geotextiles usually are long-lasting applications, bio-based and biodegradable nonwovens are not the most desired as they can shorten the lifetime of the products if they degrade too fast. For products with shorter lifespan also biodegradable materials could be a good alternative. As geotextiles require high performance, high durability is also important, to, for example, withstand changing weather conditions.

Lately, the usage of geotextiles has grown enormously especially in soil protection to protect from erosion. The nonwovens used in soil protection should increase the stability of roads and soils, thus they should be durable and long-lasting. Nonwovens in soil protection have to stand different weather conditions and not be affected by environmental exposure and degrade before their desired lifetime.

In geotextiles, the selection of materials depends on for example the hydrogeological conditions and the desired functions for the used materials[88]. Also, the desired lifespan has to be considered, as the time frame for geotextiles can vary from a few months to many years[89]. Geotextiles are commonly manufactured from synthetic, not degradable materials such as PP, PET, and PE. These materials maintain their mechanical properties for a long time, but at the same time, these materials result in harm to the environment, such as soil pollution and accumulation of microplastics[89]. Thus, especially in short-term applications, biodegradable materials should be considered. It has been estimated that non-biodegradable, synthetic materials could be replaced with more sustainable, biodegradable, or natural fibre -based materials in approximately 50% of all geotextile applications – at the moment only 2% of geotextiles originate from natural fibres[88–90]. In longer-lasting products, jute has been studied to be one bio-based alternative to fossil-based materials. As an example, Srishi et al.[91] studied the potential of cellulosic jute geotextiles with a coating to achieve superhydrophobic surface, and they found that these geotextiles have suitable mechanical properties and achieved superhydrophobicity, thus this could be one possible material to be used in roadway applications. Also, other cellulose-based or natural fibres could be feasible solution to be tested with similar or other treatments in order to achieve superhydrophobic surface for longer-lasting solutions.

6. Summary and Conclusions

As environmental concerns intensify, it is crucial for industries to embrace sustainable practices in their operations. The nonwoven industry plays a significant role in various sectors, ranging from hygiene and healthcare to automotive and construction, and since still most of the products are fossil-based, more sustainable practices are needed. There is no one solution to all nonwovens, as the nonwovens vary depending on the application from single-use to long-lasting products, and also from simple products with low technical requirements to functional products with high technical requirements. By creation and embracing different sustainable practices targeted for different product segments, more sustainable industry can be created.

In case of *single-use or disposable nonwovens*, material choices, promoting bio-based or recycled, and biodegradable or recyclable options is highly important is making more sustainable products and reducing the environmental impacts. *Multi-use nonwovens* require durable and robust materials that can withstand repeated use times and possibly many washing cycles. Therefore, high durability and repairability, together with having efficient recycling and reprocessing techniques in mind is essential in these products. Similarly for *long-life* applications, which are expected to have a lifetime of over a year, incorporating materials with high durability and resilience is highly important. Moreover, exploring innovative methods of repair, refurbishment and repurpose should be taken into consideration to maximize the products' lifespan, and possibly reduce the demand for frequent replacements.

For different application nonwovens have differences in technical requirements. When there are *low technical requirements* and no need for high functionality, use of sustainable fibres, such as renewable or recycled can be prioritized. Optimally, the materials would also be biodegradable or recyclable. Also, the process optimization is important to minimize energy and water consumption, together with reducing waste. For nonwovens with *medium technical requirements* sustainability can be improved with focusing on end-of-life management of the materials. Materials should be recyclable or biodegradable, and green chemicals should be used instead of harsh or fossil-based chemicals whenever possible. Also, repairability of the products should be considered, as many nonwovens with medium technical requirements are also multi-use or longer lasting, to keep the functionality of the materials high as long as possible. For nonwovens with *high technical requirements*, achieving sustainability without compromising performance needs also specific approaches. Extension of lifetime together with high functionality are important factors to keep the product highly functional as long as possible. Also, in-house recycling is important to capture and re-use the waste materials, minimizing resource consumption and waste generation.

In general, addressing sustainability in the nonwoven industry must be considered in all parts of the product cycle, from product design to choosing of raw materials, manufacturing, consumption, and end-of-life management. This means also thorough lifecycle assessments (LCAs) to identify hotspots for environmental impacts, and prioritize areas for improvement, and this must be made case-by-case. Thus, this report acts as giving supporting guidelines for different nonwoven segments, however, proper lifecycle assessment and sustainability considerations should always be made in addition to confirm if the new approach meets needed requirements for certain application, together with validate that the new approach is truly more sustainable.

In conclusion, there is a need for product-specific approaches to create more sustainable nonwovens in different industries. Understanding the combination of product lifetime together with technical requirements, which are specific to different segments, will guide the development and adoption of tailored sustainability strategies. As sustainability continues to be a cornerstone of every industry, making sure that different approaches account for diverse segments supports that the industry moves towards more environmentally conscious decisions.

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