July 2023

Research Gaps and Needs for the Green Transition of the European Textile Ecosystem

HORIZON EUROPE Input Paper by the ECOSYSTEX Community

Executive Summary

The sustainability transition of the European textile ecosystem requires significant advances in scientific and practical knowledge and step changes in technological capacities across a broad spectrum of material sciences, process and environmental engineering, biotechnology, manufacturing systems, information technology, social and behavioural sciences.

The present document results from a two-months collaboration of researchers, industry experts and other stakeholders involved in 23 ongoing EU-funded research and innovation projects. It summarises the main innovation trends related to the textile sustainability transition and the scientific, technological and operational challenges arising from them. It highlights the key role that publicly supported collaborative research and innovation plays in an industry sector dominated by small and medium-sized enterprises with limited means and even less in-house capacities to drive systemic change.

The report then describes in detail the specific knowledge gaps and research needs across the following 5 domains:

- **Scientific base of safe & sustainable textiles**
- **Ecodesign**
- **Bio-based textiles**
- **Circular textiles**
- **Sustainable textile production & supply chain**

For each domain the key challenges are described and in total more than 100 specific research gaps and needs are highlighted. Many of them are interrelated and require multidisciplinary approaches. The research needs described in domain 1. are more fundamental in nature and require large scale empirical research or meta-analysis of existing dispersed research by international teams. The topics under domain 32. target the practical know-how, methods and tools needed by designers and product developers to effectively drive sustainability. Domains 3. and 4. include a variety of material science and process engineering topics including demonstration, scale-up and early market introduction challenges. Domain 5. in addition to process engineering topics focusses particularly on information and data technology approaches and systemic industry and supply chain transformations and their impact on regional economic ecosystems.

To support advances in all these domains, a broad toolbox of public funding instruments and related incentivisation strategies should be employed. Foundational knowledge and data gaps are best closed through coordination and support actions funding empirical and academic research of international teams with good access to relevant industry and market data. Material and manufacturing breakthroughs are most likely achieved by collaborative (research and) innovation actions involving applied research organisations, technology and engineering experts and industrial end users. Demonstration and upscaling projects require engagement of correctly incentivised industry players including start-ups and scale-ups. Prenormative research is advised for developing standards for helping the emerging circular biobased value chains to set off. Experimentation and diffusion of novel and emerging technologies to the many SME in the textile ecosystem is best achieved through cascade funding approaches. An overarching initiative with strategic vision and a broad stakeholder engagement and governance, such as the proposed European PPP STEP2030 – Sustainable Textiles European Partnership would be the appropriate concept to ensure the multiple efforts and funding commitments are strategically aligned and continuously assessed as of their effectiveness.

The ECOSYSTEX – European Community of Practice for a Sustainable Textile Ecosystem intends to continue to organise cross-project expert collaboration, growing its experts' network and updating the textile research and sustainability gaps and needs analysis as the innovation work progresses.

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01 Introduction

This document presents the consensus of researchers, technology developers and industry innovators involved in ongoing EU-funded research and innovation projects on textile sustainability and circularity organised in the ECOSYSTEX Community. The experts collaboratively assessed the most pressing and impactful research gaps and needs to be filled to enable the green transition of the European textile ecosystem.

ECOSYSTEX, the **European Community of Practice for a Sustainable Textile Ecosystem** was founded in early 2023 from within the CISUTAC project, with the mission of:

1. Interproject collaboration by sharing best practices and exchanging/creating new knowledge to advance sustainable and circular business practices in the European textile ecosystem.

2. Engagement with policymakers to help them design effective policies and programmes and support their implementation to foster textile circularity and sustainability.

3. Dissemination towards the interested public expert community to keep them informed about the latest developments and results of EU research and innovation projects addressing textile sustainability and circularity.

ECOSYSTEX currently counts over 130 involved textile circularity and sustainability experts, representing 23 member projects from across Europe.

To enhance interproject collaboration, ECOSYSTEX formed 6 working groups around key topics in textile circularity and sustainability. The **one specifically dedicated to Research and Innovation Gaps & Needs** is co-chaired by CISUTAC via the Belgian research institute, CENTEXBEL and the European Textile Technology Platform (Textile ETP).

This HORIZON EUROPE input paper is the result of the collaboration within this working group, following 2 months of exchange among the international experts, representing the ECOSYSTEX member projects. During this period, as a first step, the key topics to be addressed have been identified in a workshop, followed by the creation of an outline, and several rounds of feedback from a smaller, then a larger group of experts. Before the working group leaders finalized the document, a webinar has been organised to accommodate an open discussion around the five key topics addressed in chapter 4: Research and Innovation Gaps and Needs.

02

Key Innovation Drivers of the Systemic Transition

The European and global textile and clothing industry is undergoing its most profound transformation since the mass production of man-made synthetic fibres and industrial-scale manufacturing and distribution of textile-based consumer products in the 1950-60s. The industrial age concept of efficient provision of a growing consumer class with affordable and fashionable textiles and clothing, taken to an unsustainable level by the cheap, fast, and disposable fashion push of the last decades, will have to be replaced by **more sustainable, value-based business models and more conscious consumption that favours quality, durability, resource efficiency, and resilience**. At the same time, textile materials have the potential to provide novel solutions for the sustainable transformation of many other sectors of the economy, such as healthcare, construction, energy and transport, agriculture, defence and security, leisure and sports.

The systemic transition of the textile sector is driven by powerful political, regulatory, socio-economic, technological and end market trends. In Europe a whole set of new regulations linked to the **EU strategy for sustainable and circular textiles** is expected to come into force over the coming years and will fundamentally change the way textile products are designed, made and taken care of at the end of their life cycle. Key aspects are ecodesign principles for durable products, separate collection and fibre-to-fibre recycling of post-consumer waste, removal of hazardous substances from textile processes and products, reduction of emissions during textile production, requirements for transparency and traceability of textile products throughout their manufacturing value chain all the way to the end consumer.

Industry structures and business models are also heavily impacted by geopolitical and socio-economic changes. There is a tendency to replace untransparent global supply chains by more **flexible regional production and distribution models to rein in overproduction and improve resilience** in the face of generally increased instability. Improvement of working conditions, fair and inclusive labour practises and the need to attract and retain a skilled workforce will require adoption of new technologies for **safer and more inclusive working environments, for lifelong learning and for attractive career development paths**.

Advanced manufacturing and information technologies including IoT and smart factory concepts, robotics, artificial intelligence, augmented and virtual reality, blockchain etc. will drive greater efficiency across all supply chain steps, will reduce waste of energy and other resources, improve workplace safety and drive collaboration and customer engagement.

End market trends are triggering important changes in products, production concepts and business models. Demand for more sustainable, authentic and/or local products is expected to increase. **Green public procurement** can be a driver of more sustainable and circular textile products for professional end markets. The ageing population stimulates greater demand for safe, comfortable, hygienic and smartly supportive products.

The increasing costs of energy, raw materials, processing chemicals and use and discharge of process water will favour **resource-efficient, waste minimising and flexible on-demand processing technologies**. The need to reduce and ultimately phase out all use of fossil fuels, whether for energy or feedstock, requires electrification of all textile processes that are still powered by oil or gas today and a much stronger focus on bio-based or otherwise renewable materials and chemicals.

Functional and technical textile products offer a wide range of solutions to actively protect the environment, make food and energy production as well as transport more sustainable and help mitigate climate change impacts. Examples include geotextiles for landscaping, agricultural textiles to mechanically protect crops and reduce pesticide use, flexible light-weight materials for vehicles or renewable energy generation systems, protective nets and barriers to minimise flood and storm impact or reduce soil erosion, membranes and filter materials water treatment, food safety or antibacterial and antiviral protection.

03

The Role of Collaborative Research & Innovation

Due to the industry structure dominated by SMEs with often very limited internal human and financial resources to invest significantly into research or higher risk innovation activities, **public funding in collaborative programmes involving RTOs and academia is crucial**. Such external research providers have traditionally acted as some kind of temporary outsourced research units for small to medium sized companies in the sector accompanying them across the entire innovation process from idea generation, technology exploration, technical development, pilot testing and validation, scale up and business development and where needed certification, training and other consulting services. Also co-development with machine, tool or chemistry providers is often needed to turn a new product idea into a scalable and marketable solution.

The constantly growing number of applications for textiles and fibre-based materials increases the complexity of materials, processes and end market requirements to be managed by companies. Long processing chains with many specialised players that need to be aligned also makes collaborative innovation approaches more suitable and promising.

Circular operations require **collaboration with new value chain partners such as collectors, sorters, recyclers and re-processers of reclaimed materials**, many of which are also SMEs and have limited experience or resources to engage in collaborative research and innovation activities. Since reusability and recyclability is often determined already at the initial design, material selection or processing stage, such collaborative innovation programmes are highly needed. A push into greater **use of natural or bio-based feedstock fibres will require strong collaboration with the agricultural, forestry or livestock producers** to ensure scalable win-win solutions.

While collaborative research and technology development programmes are important to generate new knowledge and develop new technologies, their market adoption requires many further steps to cross the “valley of death” - the stage in between the research funding and the commercialisation. New material and processing solutions typically need to undergo several iterations to demonstrate their technical robustness and economic viability at increasing scale. These **precommercial pilot scale units** are expensive to build and run and difficult to fund with market-based financing due to lack of cash flows.

Radically new technology or product approaches often require **spin-offs or start-ups** as they may conflict with or cannibalize established operations. While digital or otherwise low capital intensity start-ups are favoured by private sector risk capital providers such as venture capitalists, **capital intensive material and manufacturing start-ups should be favoured by public funding providers**.

Industry-wide adoption of new technologies or business models is a long process starting with pioneers but then slowly making their way to less innovation-driven companies or market segments. The process can be sped up by **active dissemination, technology transfer, coaching and training activities**. Such active innovation transfer services can be provided **by RTO’s, cluster organisations or industry associations**, but are not always easy to market. Therefore, public support to these activities is a suitable and generally inexpensive way to accelerate innovation.

If Europe wishes to be a pioneer in sustainable and circular textiles with potential to successfully export or disseminate European solutions to the rest of the world, such **international transfer** could already be incepted at the innovation stage **through collaborative research with non-European partners for mutual benefit**. As Europe transitions to a circular regional textile production and consumption system, many developing countries will have to deal with adverse effects from reduced need for their raw materials or demand for low-cost labour force. Innovation transfer programmes can help these countries adopt their own local circularity solutions to serve their growing home market with more sustainable textiles.

Beyond industry innovation and technology adoption, the general knowledge base among researchers, policy makers and consumers about all aspects of sustainable and circular textiles needs to be constantly improved. **Expert networks and communities of practice, such as ECOSYSTEX** are crucial to accelerate knowledge diffusion within the European textile research and innovation community and to provide **easier access for policy makers and consumer or citizen representatives (including civil society organisations) to up-to-date scientific and non-biased information and data**. Such knowledge communities can also be vehicles to launch, implement and update major new empirical data collection and analysis programmes for a better understanding of all aspects of textile sustainability.

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04

Research and Innovation Gaps and Needs

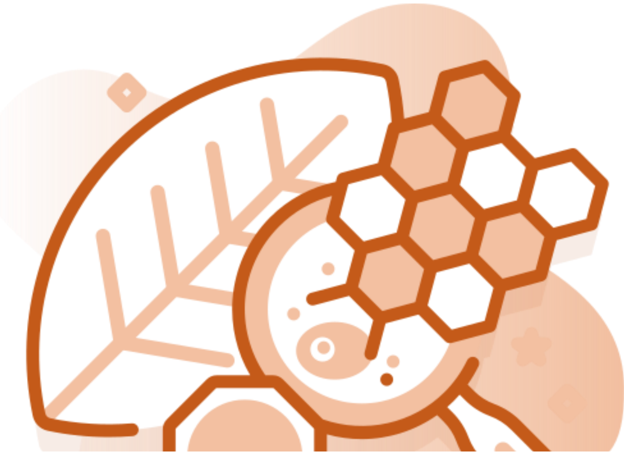
Scientific base of safe & sustainable textiles

Ecodesign

Bio-based textiles

Circular textiles

Sustainable textile production & supply chain



Scientific base of safe & sustainable textiles

Textile sustainability and circularity can only be truly advanced if actors in the textile ecosystem can make intelligent, rational and fact-based decisions to reach their objectives. The main ingredients for such decision making are (1) relevant, reliable, correct and up-to-date data, (2) concepts, methods and tools that employ the data to make assessments, simulations and optimisations and (3) a broad and clear understanding of drivers, enablers and inhibitors of systemic change at the required scale.

Currently we are very deficient on all 3 dimensions that are necessary to understand and manage the sustainable textile transition. Most HORIZON-funded research and innovation projects contain some tasks or work packages tackling such underlying knowledge elements, but their resources usually dwarf the technology development work packages and often too narrowly serve the specific knowledge and data needs for the specific materials, processes or applications targeted in the project. Larger scale empirical and desk research and international coordination type projects are needed to build a solid knowledge base required for more impactful technology development, smarter policy making and better business model and strategy development.

Data

- Collection, processing, analysis and utilisation of all relevant textile sustainability data and guarantee of the F.A.I.R. principle while safeguarding confidentiality and intellectual property of researchers, creatives and businesses.
- Examples include:
  - Textile material and related resource flows from resource extraction to the end user
  - Comparable LCA data on a broad range of textile materials and products
  - Detailed textile waste flow data including volumes, product types, material composition, channels and types of waste management
- Research related to semantic web related toolsets (semantic web-capable resource description framework vocabularies, possibilities and limits of knowledge graph use for gaining circularity critical KPIs from the web-based data resources).

Concepts, methods & tools to model textile materials, processes & products, and to assess their safety & sustainability

- Ontologies, frameworks & models to describe, simulate & communicate textile materials, processes, value chains and product life cycles
- Designing and adapting methods and standards to calculate environmental impact assessments, life cycle analysis (LCA), social LCA, life cycle costing (LCC), toxicology studies and product environmental footprint (PEF) calculations for textile materials/chemicals, processes and products, while keeping the methodology in line with other circular and bioeconomy sectors
- Integrate the safe-and-sustainable-by-design (SSbD) framework, developed by the Commission, for assessing the safety and sustainability of chemicals and materials, based on REACH and with a specific focus on advanced and highly technical textile materials and processes used in technical end markets
- Research into release, dispersion, human health & environmental impact of fibrous microparticles unintentionally released from textile products during production, use and end of life and potential mitigation strategies
- Develop simple and practicable science-based methods to assess the sustainability of textiles (including e.g. microplastic detection)
- Develop methods to increase transparency and support decision making in industry towards safe and sustainable textiles

Understanding technological and non-technological drivers of systemic change and wider impacts of the systemic transition

- Understanding of systemic drivers, enablers, barriers and impacts of circular/bio-based transformations in all aspects of the textile ecosystem (scenario development, modelling of complex system changes, interactions, externalities, feedback loops, rebound effects…)
- Designing EPR systems incl. eco-modulation, modelling of their implementation and measurement of impact
- Research into textile & fashion user/consumer/public procurement behaviour as driver or inhibitor for increased textile sustainability & circularity and basis for successful deployment of more sustainable business models
- Develop and analyse new sustainable business models (e.g. circular business models) and policies to prevent overproduction and overconsumption with attention to actors who can make or break a business model in combination with LCA and S-LCA best practices e.g. social economy.
- Systematic material and process research in order to produce - with lowest resource consumption and lowest mixtures of materials - fibres, yarns and fabrics of highest functionality, quality and durability.
- Understanding of wider global societal impacts of an effective transition of the European textile ecosystem to a more sustainable and regionally circular operational model such as resource access, employment opportunities, knowledge transfer and export income evolution in major current supplier countries of textile and clothing products to Europe, avoiding negative local effects and ensuring smooth and fair transition scenarios.

Ecodesign

A very significant part of a product's impact is determined at the design or product development stage. Textile and fashion designers and product developers have typically good knowledge of the needs and desires of their customers and end users, but often lack a deeper understanding of materials, production processes and the realities of the manufacturing supply chain. This systematically leads to suboptimal or occasionally even outright disastrous decisions with heavy impacts on cost, efficiency and waste generation at all stages of a product's life cycle. **Accessible material data, relevant knowledge, adequate tools and smart incentives** can massively improve decision making at the design stage and lower the cost and impact of poor design choices. Better design strategies that optimise for desirable product characteristics such as longevity, repairability, recyclability or biodegradability and tools that help implement these strategies in the daily practice of the designer and product developer must be developed, user-tested, widely disseminated and trained.

A much further **virtualisation and digitisation** of the design process must be established. Design systems combining product functional and aesthetic creation tools with largely automatic rapid simulation, comparison, assessment and optimisation of manufacturability, production and logistic footprint, product performance during use and end of life must be developed. Digital twins of products, processes, production lines and entire factories or supply chains have great potential to optimise textile production not just for cost and efficiency but also for many factors determining sustainability and circularity.

Understanding of design impacts on safety, sustainability and circularity of textile-based products

- Develop methods to increase transparency and support decision making in industry towards safe and sustainable textiles Assessments based on the known circular design principles (9Rs)
- Methods to assess and compare potential lifetime of textile products
- Understanding recirculation for garments and components as contribution to extend lifetime and interaction with business models enabling shared use and product service systems.
- Evaluating hazards and fate and exposure of materials and auxiliaries in sourcing, work environment, use phase and end of life to understand safety related tasks
- Framework of circular design principles per different textile product categories (maybe also material types) vs. TRL of recycling technologies; current, near-future, far-future

- Importance of cross-circular (multidisciplinary and multi-stakeholder) dialogue to enable systemic understanding of impacts (Systemic Materials Innovation)
- Importance of time factors on the impacts of design decisions, now, near and far and the potential role of 'cascading' (I.e. how do we design a 10-year garment for an unknown future recycling system?)
- Education and seeding the next generation of designers
- Definition of terms (glossary)

Design-aspects of innovative materials/applications, practical application of the SSbD framework in textiles

- Developing good practices about how/in which format to deliver complex technical and chemical requirement information to designers
- Understanding the challenges to incorporating alternative design strategies at the design stage (I.e. organisational challenges, risks, different scenarios of design practice)
- Mapping gaps and trade-offs in approaches intended for environmental health and safety assessment vs sustainability assessment.

ESPR-related issues such as design for durability, recycling, reuse, repair, reduced fibre release…

- Mapping gaps and trade-offs in approaches intended for environmental health and safety assessment vs sustainability assessment. Definition of a common and standardised semantics, ontologies and data model that eases the integration between digital solutions and their interoperability to support the ESPR
- Implementation of the Digital Product Passport (DPP) to ease the access to information about product environmentally sustainable and digital content to promote informed choices in both B2B and B2C environments
- Commonly agreed (or even standardised) methods to define and measure longevity of textile products.
- Piloting and early market implementations of circular design approaches at industrial scale through demonstration projects.
- Advanced IT/AI tools for design, simulation, assessment, valuation and sorting & optimisation of textile products, their use and life-cycle impacts, collaborative human-AI design

Digital and virtual design tools combined with expert systems for sustainability optimisation

- Development and utilisation of digital twins of textile products, processes, factories and supply chains
- AI-based expert systems for simulation, assessment and optimisation of sustainability and circularity parameters of new products
- Piloting, upscaling and training for use of digital design and sustainability optimisation systems for all types of textile-based products and manufacturing processes.

Bio-based textiles

Making the switch to a full bio-based textile value chain requires innovations and adaptations all along the value chain. Here we list the main elements where we see remaining challenges, covering feedstock, fibres, additivation, finishing & coating, functional & economic performance, End of Life and sustainability/impact assessment. For clarity: with bio-based textiles, we refer here to the use of 'biosynthetics', i.e. bio-based polymers and to manmade cellulose fibres (MMFC).

Feedstock

Suitability, availability and sustainability. Sourcing from biomass actually covers a wide range of materials from nature. Depending on the biorefinery/biotechnology deployed, one can obtain basic chemicals/chemical building blocks but also monomers, polymers or natural (micro)fibres. Some biomass sources are already well investigated. But extra research is needed to map which biomass in combination with which biotechnology results in intermediates with the highest potential for the textile value chain.

Especially exploring the potential of common biomass waste or side streams that are available in large amounts need to be thoroughly investigated. Work on secondary raw materials sources (e.g. biowastes, no competition with food crops/wood), yielding a high efficiency and with a sustainable production process. A clear need for cost competitive bio-based raw materials as current ones (e.g. PA11, PHA) are still considerably higher as conventional PA and PET.

Specifically for natural fibres, additional knowledge is needed on the availability and suitability of alternative fibre sources (e.g., from grasses or agricultural residues) and their sustainable use for the (bio-)economy. This to alleviate pressure on cotton and wood as main sources or to deal with the decreasing availability of flax fibres (and linked rising prices) due to increased demand from Asia. A potential interesting category of biomass could also be valorising crops that are used for depollution of soils and/or regenerating nature.

Biorefinery innovation together with (other) bio-based feedstock producers and users can be exploited in more depth. Some of the more promising options: exploitation of side streams from other industries, processing of post-consumer biowaste, improved purification of marine cellulose resources (e.g. removal of salts-ash), cellulose extraction and refining processes for alternative fibre sources or novel processes for obtaining building blocks for synthetic bio-based polymers with potential for use in textiles, e.g. for fibre, coating or finish.

Collaboration and innovation with relevant stakeholders and industrial symbiosis forms the basis for deploying bio-based textiles and can further create mutual benefits and shortcuts to market. Items to be considered:

- Agricultural, forestry and aquaculture innovations for more cost-efficient and sustainable fibre feedstock production and harvesting, e.g. potential use of empty greenhouses to grow feedstock.
- Innovations required to improve consistency of quality of natural fibres and combat climate effects. Potential use of empty greenhouses to grow feedstock.
- Build on existing production capacities for man-made cellulose fibres, also adapt these processes to alternative feedstocks.
- Look into synergies with the paper industry, given the vast expertise with cellulose.
- Dealing with seasonality – several types of biomass are only available during a limited period of the year.

Fibres

Research is needed to widen the range of bio-based fibres on the market. A high potential is seen for thermoplastic materials that can be processed with (minimally refurbished) existing filament extrusion equipment. Examples could be thermoplastic cellulose or development of PHA, the later having the option to obtain fibres degradable in a wide range of environments. Other identified promising developments: development of regenerated cellulose fibres that are strong enough so that blending with PET or nylon (bio-)PA is not required (to ease recycling), development of a bio-based alternatives for elastane, use of PBS for home compostable textiles or PEF based textiles for a range of (technical) applications.

Also for bio-based fibres already on the market an important topic remains their further development and optimisation. Of special interest is the study of the long-term evolution of their properties (order 1 to 5 years or even more for certain applications) as these will deteriorate over time in a different manner as conventional ones. Example: there are indications that certain PLA fibres might lose their strength after a couple of years more strongly as expected.

Additives, finishings & coatings

Next to the fibres, it is crucial that the other steps in the textile manufacturing process also become bio-based. This implies that further development is needed for the (bio-based) dyeing/printing of novel bio-based fibres (e.g. washing and light fastness). Also for common textile functionalities, we need bio-based solutions: water repellency/proofing, dirt repellency, UV shielding and anti-microbial finishes. But also for lamination and coating, including the development of bio-based (and preferably reversible) adhesives for laminated (bio-based) textile structures (e.g. heat insulating inner layer and fashionable/waterproof outer layer). Of special attention here is providing barriers for chemical substances needed in PPE and providing flame retardant finishes.

On the other hand, a new set of processing technologies opens up: bioprocessing of fibres and textiles and related biochemistry. The novel possibilities for textile material processing and production needs to be further explored, including process upscaling and intensification and manufacturing aspects (e.g. uniformity) but also the application of the novel processing techniques on conventional textiles. Examples: enzymes to break down synthetic fibres, enzymatic bleaching or bacteria which produce natural dyes.

Performance

- **Functional performance:** application and end-use related knowledge & optimisation. Even if the goal is to mimic existing textile material properties via bio-based materials, there will *not* be a full match and properties will deviate, e.g. on processability because of friction, temperature resistance,…. Therefore, it will be needed to investigate on the one side current processing conditions and to adapt current production equipment and on the other side end product requirements /use guidelines might have to be adjusted. This is needed in view of the properties of the bio-based fibres, both for those already available on the market and for those emerging.
- **Economic performance** matching of bio-based or bioprocessed textiles with conventional (fossil-based and/or conventional) materials. As mentioned before, for several bio-based materials there might be a cost disadvantage compared to large scale produced fossil-based ones. This scale difference will persist for several years to come. Therefore, more insight and information on matching the 'right' bio-based fibre/finish/coating with the 'right' application is needed.

End-of-life (EoL) management of bio-based textiles

For bio-based materials the EOL management will be key, similar to traditional materials. To minimise their impact, the various R-strategies and their order remains valid. This means that design for recycling and more in general the guidelines for sustainable products will apply. Below we list some aspects for study.

For still a considerable time the share of collected bio-based synthetic textiles in waste streams will be fairly small (except for man-made cellulose fibres). Therefore, on short time solutions are needed on how to deal with 'bio-based impurities' in traditional streams. Ideally one find solutions for the recyclability of bio-based blends (e.g. cotton/PLA or viscose/PA).

Large scale future introductions of novel bio-based polymers (e.g. of bio-based polyesters like PEF) into the textile chain should be accompanied with a clear strategy on how to aggregate or deal with these textiles at end of life.

Next to 'classical' recycling technologies (mechanical, chemical), novel technologies might be better suited for bio-based textiles, e.g. enzymatic or other biotechnology-based processes.

Biodegradation is a potential EoL option but should be treated with care. Clearly, it is not the most resource efficient solution but it can offer an elegant EoL in cases where textiles are too strongly mixed with organic matter to still be separated and recycled. This will most likely require tailored biodegradation, i.e. the biodegradation only starts after a certain time or via a specific trigger to prevent that the biodegradation already starts during the lifetime of the product and leads to (preliminary) failure. Further, a better understanding is needed of the influence of the material morphology used for the product on the biodegradability of the material. Indeed, biodegradability dynamics is not an intrinsic material property but depends on the shape of the item (e.g. aspect ratio of the part, fineness of the fibre) undergoing biodegradation.

Microplastic/fibre generation (during manufacturing, washing, use) is also an issue for bio-based textiles. Solutions are needed for its prevention (e.g. application of bio-based finishes, alternative manufacturing techniques) but also for its remediation. For the latter, especially triggered biodegradability has a large potential, e.g. by adding the functionality of degradation in salt water or by reaction to specific triggers present in soil or aquatic environments.

Impact studies of bio-based textile materials and products

Additional studies are needed on environmental impact of bio-based textiles compared to conventional materials, to provide science-based evidence to steer towards the most sustainable direction. This to signal in time unwanted side effects of biomass sourcing (e.g. on land use or energy use), to be able to compare various biomass options, and to select the most sustainable ones. Indeed, not all bio-based solutions will be sustainable, and LCA and LCC aspects should be mapped, both for bio-based fibres and finishes/coatings. Also insight is needed into potential social and societal aspects.

Further, better understanding is needed on how to compare 'renewables' with 'fossil-based' to ensure a level-playing field. Also development of (EU or worldwide) standards and of methodologies on how to make these various assessments.

Circular textiles

For establishing circular textiles, recycling technologies need to be optimised and made more robust towards input streams. But also the related supporting activities like collection, sorting & separation, and cleaning & pretreatment. But even before that, efforts are needed during the actual lifetime to better understand how textile product and material use can be intensified and extended.

Lifetime intensification and extension

Technical, organisational and behavioural research into life-intensifying and life-extending strategies for textile products such as second and/or shared use, care & maintenance, repairing or refurbishing.

- **Technological developments.** Enabling re-use, re-make, re-furbishing, aided by ecodesign (see also section 4.2). Special attention to ease repair actions (e.g. via automatisation, via design for 'repair') so that repairing becomes also economically feasible for lower value items. Research into extended use phase via improved and more fitting maintenance and care, e.g. tailored washing and cleaning procedures but also rejuvenating functionalities.
- **Set up of capacity**. Next to technology, also novel value chains and business models need to be setup for lifetime intensification and extension. Explore the opportunities offered by repair, re-make and re-furbishing for micro-factories, for social enterprises, for inclusive employment.
- **Citizen behaviour.** More in-depth knowledge on consumers' perception towards clothing and decisions to buy and discard, but also to novel ways of consuming textiles: sharing, swapping, renting,... Understanding consumer behaviour towards textiles in view of the increasing awareness of the environmental and social impact of textiles.

Collection & sorting

Technical and organisational research into industrial, pre- and post-consumer waste collection and sorting.

- **Collection – devising schemes for maximising amounts & minimising value loss**. Need for setting up easy access collection points for both consumers and companies to discard waste textiles. Understanding to what extent collection (type, place, guidelines,...) determines the amount and quality of what is collected. Studying collection methods in relation with the 9R model. Using these insights to devise collection channels that maximise the value of the collected streams, or at the least prevent value destruction because of collection.

- **Sorting – finetuning for optimised aggregation of textile waste**. Typically the first sorting step involves splitting into what is fit for reselling in EU (or elsewhere) and what is not. In the latter case more and more the material composition of the textile item is determined using for example near infrared (NIR) technology. For the reselling stream, imaging technology accompanied by algorithms helping to assess the resale value (e.g. brand, style, level of wear,...) are needed, ideally combined with input from consumer behaviour and perception studies to determine what is actually 'resellable' and what not. For the recycling stream, further development of automated sorting technology (e.g. for reliable multi-material identification and grouping) and having public standardised databases for material recognition. Enlarging the options towards sorting for refurbishing, remanufacturing and upcycling, e.g. hardware and software to fully automatically enable sorting out fabrics of a specific material, colour, type and (minimum) size. As circular material use will become more and more common, an important aspect will also be the assessment of the quality of the waste (e.g. because of the number of cycles), thus determining what type of recycling is most appropriate.
- **Logistics and infrastructure planning**. Research is needed to assess the optimum between reselling, reusing and type of (cross-sectorial) recycling, taking into account the local situation (e.g. urban vs rural) and time ('now' but also on medium and long term). This will in turn allow to calculate the required collection, sorting and processing capacity and infrastructure and the related logistics that are needed.

Textile recycling

Cleaning/pre-treatments, mechanical, thermo-mechanical, chemical and biochemical recycling processes and supporting activities.

- **Improvement of actual recycling technologies.** At the core of textile recycling are the main technologies: mechanical, thermo-mechanical, chemical and biochemical processes. These four technologies all have their strengths and weaknesses but for all four research is still needed, like more robustness towards input material. Further also increasing recycled fibre lengths (for mechanical) and scaling up via large scale pilot demonstration (for chemical and biochemical). Biodegradation should be further explored as recycling option for specific cases, e.g. in case of intimate mixing with organic matter (because of the use phase). Enzymatic recycling methods for synthetic and natural fabrics.
- **Cleaning and pre-treatments.** Research into when, for which recycling steps, and what type of cleaning is needed. Further (automation) technologies for pre-treatments to make the waste stream fit for the recycling process. This includes processing steps like identification of 'issues' and smart cutting and/or smart disassembly using (thermally) triggerable seams for easy removal of textile accessories like zippers and buttons. Also removal of colourants (how to remove dye/ink) and of

coatings. Detection and removal (or reducing their amount sufficiently) of legacy materials that could be present in colourants, finishes or plasticizers that are no longer to be used within EU.

- **Separation for handling multimaterial textiles** of e.g. fibre blends, coatings, prints, laminates. This type of textile materials was already mentioned at the sorting phase as they are expected to form a challenging but large fraction of the textile waste. Studies are needed on how to deal with these: how to realise the highest value retention, how to separate coatings from fabrics, how to separate laminated fabrics, how to separate blend of cellulose and polyester, how to separate elastane from natural and synthetic fibres blends. Multimaterial textiles that cannot be separated or less frequent occurring material combinations will be sorted out and grouped together and also for these streams a sustainable circular solution sought be researched, e.g. pyrolysis.
- **Cross-sectoral symbiosis** for treatment of complex waste streams, effective feed-in of textile waste into other product recycling systems or feed-in of non-textile waste into textile recycling processes. Textile to textile recycling will *not* always be the optimal solution, therefor need to research what the alternatives are and how sustainable these are. Scanning for upcycling/upgrading the materials during recycling towards specific needs for textiles e.g. by adjusting polymer viscosity to filament extrusion requirements. Also not excluding the suitability of downcycling in certain cases, e.g. at which point can food packaging be downcycled to textiles, etc. Need for setting up centralised recycling chains, giving easier access to various sectors to tap into the streams.

Transversal aspects

- **Safety – preventing harmful substances in circular material use.** Whenever a textile product or material is assessed for circular use it offers an excellent opportunity to check for potential legacy substances. Indeed, to ensure safety this should be checked before reselling/reusing/recycling. This implies we need methods to quickly scan/detect for legacy substances during (manual/automated) sorting so that (potential) non-fit items can be singled out. Technologies to remove the legacy substances from the materials during the separation and/or recycling steps are needed as well as safe end of life scenarios for items that cannot be recycled.
- **Human resources – attracting & training people for realising circular textiles**. The novel processing and manufacturing steps needed for circular textile value chains imply the need for people with novel skills. Development of appealing, interactive curricula and training material will be crucial to attract (young) people. This to ensure the workforce for implementing circular textiles is available in Europe.
- **Standardisation – defining circular input & output streams and related methods & terminology.** To set up the required novel circular value chains, standards are needed defining the various input / output streams (like for dealing with polymer impurities, e.g. small fractions of polyamide in recycled polyester), including also methods on how to measure these, using agreed-on terminology. Further, prenormative research for defining and determining the fraction of recycled content in products and for performing environmental impact studies.

- **Environmental impact studies – identifying circular strategies with the least environmental impact.** Sustainability assessment of the full lifecycle, i.e. spanning collection, sorting, separation and recycling/reuse, is crucial as it allows to assess circular solutions versus linear materials use and to compare various circularity strategies. In both cases, the output of the studies will allow to select the most sustainable strategies, to identify so-called 'hot spots' for improvement and to motivate why to implement circular strategies. Of special interest are assessing the impact of recycling on microfibre/plastic release, build-up of a database of the CO2 footprint of recycling and related activities and to develop a deeper understanding of the main environmental impact contributors in a circular value chain.
- **Green and circular public procurement – setting up of realistic & clear tender guidelines**. Public procurement entails several textile products, like for PPE (for fire fighters and law enforcement), for the military and for the public medical sector (workwear & hygiene textiles). Research is needed to investigate how the tendering procedure can be used to drive textile sustainability, how to boost recycled content, how to foster a systemic change. The findings should be translated into guidelines for public authorities (at national, regional and local level) on how to set up tenders for circular textiles.
- **Ecosystem building – bringing together circular textile value chains.** Mapping the actors in the value-chains, their role, their interaction, how they achieve targets and create value. Evaluating the impact of the transition and the rebound effects for the local/regional economy but also the worldwide implications. Identifying and including the externalities in the value chains. Taking a broader focus and a system perspective.
- **Digitisation – development & pilot testing of digital enabling technologies for textile circularity**. Efforts ongoing to establish the Digital Product Passport. From textile side, need to see how to best make use of the DPP, e.g. for information sharing and for supporting open databases. Pilot testing on data collection, analysis and expert decision support systems, traceability solutions, knowledge and technologies for cost-effective and user-friendly digital product passport applications for circular textiles. How to make the info available at all steps in the value chain. How to transfer the information linked to a product to the material streams into which it is separated for recycling.
- **Bio-based materials – integrating emerging bio-based materials in textile circularity.** Except for MMFC, bio-based materials in textile waste will remain relatively limited on short and medium term. Therefore, we need strategies on how to specifically sort/recycle bio-based materials given the low quantities during the transition phase (economic feasibility). On how to determine the level of acceptable contamination of bio-based fraction in fossil-based materials but also vice versa. Solutions for dealing with mixed fossil/bio-based fibres in current sorting/recycling facilities. So, a strong need to establish an intimate connection between bio-based & circular materials.

Sustainable textile production & supply chain

The textile environmental impact stems not only from the materials sourcing, but to a larger extent from production, logistics and use. Here we consider these latter aspects and identify in a non-exhaustive way topics where dedicated R&D can help to improve the sustainability.

Net zero emission production

- **Energy use:** going renewable and becoming more efficient. EU strives to zero emission production. A key element is the energy use. The textile sector will benefit from developments and efforts in other sectors, e.g. via the use of renewable energy or the ability to use more energy efficient equipment and the electrification of oil and gas-powered processes. But, the textile sector will also need to contribute. This by developing novel and mainstreaming emerging processing technologies, e.g. low temperature and heat recovery processes. Further, research into use of current technology to monitor the industry plants to get the actual energy use data, develop algorithms, and planning software to devise energy efficiency plans, e.g. (increasing) producing when low demand for electricity. Deployment of systems enabling to monitor the actual energy use in real time per machine/process.
- **Resources use.** R&D for resource-efficient, wasteless and pollution-free fibre and textile processing, requiring minimal or even no water or solvents. This involves for example the study on the use of smart low-cost measurement systems and online resource consumption and quality control systems. Also solutions for eliminating the use of for examples additives that are not sufficiently in line with the Do Not Significant Harm /SSbD principle, which can be via replacing them but also by altered processing making their use obsolete.

- **Secondary raw materials use.** An important step is the ability to integrate in the production the use of secondary raw materials. As these materials often show larger variability in properties, a higher degree of contamination and a wider range of contaminants, more robust process technologies need to be developed, relying more on close monitoring of the production process and algorithms that can self-regulate the process conditions within set boundaries. Also development of (standardised) methods for assessing the quality of recycled materials and in some cases even settling the related nomenclature.

Advanced automatisation & robotisation

For competitive textile production in EU, a high degree of automatisation will be required, mainly for decreasing the manual labour cost. Further, the scale of deployment will be smaller as currently the case in cheap labour countries. So, there is a clear need for further research on how to introduce into the textile sector automated and robotized production technologies. Also extending microfactory concepts, building further on technologies that enable small lot sizes and that require minimised loss of production when switching from one product to another. Further also on-demand production concepts and technologies for reduction of stock and unsold goods. And technologies that allow in an economic way production of made-to-measure items. Emerging solutions exist but they are in need of optimizing, enabling their widespread use. Such technologies will (help to) prevent manufacturing unsold goods, a first hurdle to take towards a more sustainable textile sector.

On the other hand, we need highly automated manufacturing techniques that can help realizing circular material use, i.e. for disassembly, for repairing,… of textile products and materials.

Digitalisation

The digital transformation is a crucial and large topic in itself. Here, we assess it from the view on how digitization can help to become a circular and bio-based textiles sector. Research needs exist at various levels and at the various steps in the value chain. The key challenge is to promote integrable and interoperable solutions to ease the data sharing.

A core element is the **digital product passport (DPP)**. According to upcoming regulation, textile products will need a DPP. The definition of its content is already on-going. However, there is the need to define the data repositories where the DPP information will be stored to be searchable when machine-readable. Also the legal framework or reference for the data collection and declaration needs to be put in place to support product data faithfulness to support the DPP. The necessary evidence needs to be collected to enable a clear regulation on mandatory data to provide for traceability/DPP.

Traceability is crucial and efforts are needed to set up schemes and systems for materials and products transparency, covering physical and digital aspects. Conventional electronic labels/tags connected with traceability IT platforms could be (the start for) an implementation method, but other technologies such as chemical or biological material/product markers should also be studied. Irrespective of its implementation, it will need testing in the real world. Traceability labels readable by consumers are required too enabling them to check 'the story' of the items they (plan to) purchase. Standardized data models to trace the whole value chain underpinning such systems are needed. Promote traceability systems to collect the necessary evidences for the origin declarations to avoid false declarations.

Data availability. Research on data generation with the right data exchange standards and data processing along the whole value chain, including the data access and processing at the Point of Sorting and Point of Recycling.

Developing novel circular business models, e.g. by setting up sharing platforms. Exploration is needed on how digitalization and the DPP can create novel business opportunities, e.g. by offering novel services for maintenance, for repair, for refurbishing and for sizing. The latter could seriously decrease the number of returns when online shopping.

Logistics

Logistics is a crucial element and has its own challenges but also opportunities to contribute to a more circular and sustainable textiles sector.

For reaching circularity, we need to investigate the **setup of collection channels** and sorting guidelines, e.g. taking into account the specific geographical situation (urban vs rural); season (winter vs summer) and the availability of required (automatised) infrastructure. Based on this, development of guidelines and blueprints on how to organise collection locally.

Also **integrating biomass into the textile value chain, entails logistics aspects**. Starting from existing mapping of which biomass is most suitable to transform into raw materials for the textile sector (and where it is and at which time), schemes need to be developed for efficient collection of biomass and for aggregation into processing plants.

In general, we need **supply chain digitalisation** for increased efficiency, optimised supply chain planning and flexibility, in line with on-demand production concepts and technologies for reduction of stock and unsold goods. Another topic is how digitisation can help on-demand production and logistics incl. return logistics and other value-adding services such as purchase and use advice, repair, resale, rental, sharing, etc.

Resilience and strategic autonomy

We need strategies for **reduced international dependencies for critical materials**, e.g. via novel processing steps eliminating the need for raw materials or via recovery of (critical) materials from waste or via research in smart end-of-life management.

We need concepts and scenario development showing how **increased resilience** and a greater strategic autonomy of the European textile ecosystem can be achieved, e.g. by better understanding potential bottlenecks at materials and production levels. Impacts of a more autonomous regional European textile ecosystem on the rest of the world should also be studied.

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Funding requirements and support instruments

Transitioning to a fully sustainable textile production and consumption system in Europe is daunting. It will require all stakeholders to adopt novel approaches which initially will inherently be risky, be it financial, be it reputational. Two examples: for establishing the necessary capacity for textile recycling it is estimated that ca €7bn of investments are needed (McKinsey, 2022); designing and producing for quality and durability has the largest positive sustainability impact on textile consumption (OVAM, Centexbel, VITO, 2022) but to market this, brands need to deploy novel business models, without losing the customers. So, wide public support for the transition is a must, as well as adapted logistics and product-services, which clearly shows that there are not only technological challenges. To tackle this wide range of challenges we see a large potential for EU-wide funding instruments, especially of the Horizon framework programme, to play a catalysing, nurturing and boosting role.

'Horizon' (i.e. referring to Horizon 2020, Horizon Europe) is the EU general framework programme for Research and Innovation. It covers fundamental breakthrough research as well as innovation development to boost company competitiveness. Although project types exist that focus on one or a limited number of partners, the typical EU projects we refer to are **collaborative multi-disciplinary projects** involving commonly 10 to 15 or more partners. The topics of such (current and past) projects cover the whole circular textile value chain (design, materials, production, product performance, collection & recycling), the scope ranges from low to higher TRL (covering 3 to 8), participation of all types of players is encouraged (large companies, SMEs, universities, RTO's, associations, NGOs, public authorities,...) and it is open for all EU countries and many associated countries in the Greater European region. Although exceptions will always exist, the evaluation procedure is generally conceived as of high quality and impartial. So, it is fair to state that Horizon is very fitting and attractive for funding collaborative projects on topics supporting the transition to sustainable textiles manufacturing and use.

Because of its attractiveness, Horizon is also highly competitive, which is its main disadvantage. Another disadvantage is that textile related calls stem from various 'origins': topics can be found in several clusters (e.g. Cluster 4 – Digital, Industry & Space, Cluster 6 – Food, Bioeconomy, Natural Resources, Agriculture and Environment) and within these clusters call topics stem from different sub-themes (e.g. RESILIENCE, TWIN TRANSITION, CIRCBIO,…). This makes it a challenge to find the potential calls in time and to act on the opportunities they offer. Furthermore, the size of -funded collaborative projects is usually in the range of €5-15 million, which means that very large (e.g. for pilot infrastructure) or very small (to help starting companies) projects are not covered.

Continuing on the above assessment of Horizon project types, we now phrase some suggestions from textile side for the type of projects and the benefits of having a dedicated public private partnership.

Cascade funding for low threshold projects boosting (very small) textile SMEs and start-ups. Cascade funding offers to beneficiaries low application thresholds, shorter time-to-grant and reduced administrative (reporting) burdens, aspects which are particularly beneficial for the textile industry as the vast majority of the companies are very small SMEs (only 0.2% are large companies, more than 88% are micro companies, i.e. less than 10 employees – Euratex 2022 data). Moreover, the overarching project handing out the cascade funding typically provides 'smart money', i.e. the (lump sum) funding comes with expert guidance tailored to the need of the receiving SME. Because of this, we would recommend cascade funding projects (e.g. like INNOSUP) for stimulating the transition also at small scale, or even micro scale, companies. Due to its rapid time to grant and smart money concept, it is also particularly fitting for start-ups of which there are a growing number especially piloting new business models and exploiting digital technologies that established companies struggle to adopt. With EIC funding highly competitive and often dominated by start-ups in "high-tech sectors", cascade funding would be a very suitable complementary support instrument for textile start-ups.

Large scale flagship (de-risking investment) projects. The typical Horizon project allows going to TRL 8 and limited pilot scale. But for quite some of the developments needed for going to circular textiles even after such piloting actual commercial deployment and related scale up still requires a high-risk investment given the novelty and the uncertain economics (unpredictable, highly dynamic textile waste market). Therefore, fostering such large-scale infrastructure projects via flagship type projects is suggested. We favour large projects, aiming to implement large infrastructure at industrial pilot scale, carried by industry, requiring a detailed preliminary business plan of considerable size (€15mio or more). These 'flagship projects' would resemble those already currently in practice in CBE.

Backup funding via a concerted effort of MS funding for proposals that score well above the threshold but that do *not* get Horizon funding. Because of the competitiveness, several excellent projects that score well above the threshold for funding are currently not funded. Efforts have already been made to pick up such proposals via other funding means, e.g. via funds on national or regional level. This was the case with the 'seal of excellence' which was handed out for SME instrument proposals that were not funded but had a score above the thresholds for being eligible for funding. In general, it would be beneficial to set up a scheme in which high scoring proposals that qualify for funding but due to the competition do not get funding can be channelled to alternative funding mechanisms via regional or national funding. Although the latter might be an administrative challenge, MS could collaborate and put together funding for this. As it ensures their means will go to high quality multi-disciplinary, multi-country projects that underwent a thorough evaluation process. Especially as it would only concern a small fraction of the means available at the regional or national levels. For example Lithuania and Malta are following this line for providing a backup mechanism by shifting ERDF funding.

STEP2030, a Public Private Partnership (PPP) dedicated to sustainable EU textile production and use, covering technical textiles and fashion. STEP2030 is a EURATEX initiative to realise a PPP for the textile sector. **Vision: a public private partnership to make the EU the first region to implement truly sustainable textile production and use**. Main objectives are to create the knowledge and technology base for competitive sustainable textile production within the EU, for the circular use of renewable materials, for the prevention of harmful substances, for net zero emission operations and for fair value chains with a local inclusive focus.

The call topics of the textile PPP would focus on realising the above-mentioned vision and can be enlarged to other goals coming to the twin transition of the sector, including the gaps and needs identified in this document. Also textile-related topics that are currently being presented via Cluster 4 and Cluster 6 could be integrated in the Textile PPP.

The PPP would cover 'upstream' aspects, i.e. the sourcing of the raw materials needed for the sector by teaming up with the relevant sectors (chemistry, agriculture, forestry…). Of special interest here are potential synergies with the European agricultural sector and programmes supporting innovation in growing, harvesting and processing crops producing biomass for the textile sector (see also section 4.3-).

On the other hand, **the PPP could integrate 'downstream' aspects**, i.e. sustainable product use and end of life solutions. The latter would include topics related to technical textiles as well as to consumer textiles (clothing, interior). In both cases also the use phase (maintenance, customer/consumer attitudes,…) should be covered.

International dimension. The textile sector is a truly global sector and given the large import into EU, but also the considerable export of textile materials, striving towards a (more) level playing field worldwide is a necessary condition. Funding schemes fostering such balanced international collaboration, e.g. via standardisation, via environmental and social assessment methods or via common Safe-and-Sustainable-by-Design principles should be part of the PPP. Highly relevant are impact studies of EU legislation on global textile supply chains and non-European economies and natural ecosystems.

Targets definition. Finally, via a Textile PPP also a governance structure would be set up, that could help to define common targets for the sector and to ensure that EU-wide efforts are aligned, thus preventing duplicated work and/or wasted efforts. For the common targets, a clear goal could be to the development of monitoring systems, e.g. for use of recycled materials (as already exists for the plastics industry in the form of the Monitoring Recyclates for Europe (MORE) platform fun by the European Plastic Converters Association EuPC) or for greenhouse gases reporting in fashion industries. This would lead to a uniform and trustworthy assessment and reporting scheme, that help to prevent unsubstantiated green claims, and can give a science-based targets.

Mapping and scenario building. This would also be the body to define study topics dealing with more fundamental aspects of the textile sector, e.g. for the mapping of material streams or for developing long(er) term scenarios for the textile sector, serving both as basis for industry investments and for EU policy making.

Summarised, by combining the above elements, the public private partnership can be a key enabler to realise the vision of making the EU the first region to implement truly sustainable textile production and use.

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Conclusions

The sustainability transition of the European textile ecosystem is a multifaceted, multidecade systemic transformation that needs to be built on a sound scientific knowledge base and broad material science, processing, manufacturing and information technology foundation.

As of today, many elements of this knowledge and technology base start to emerge but they are not yet firmly established, not systemically connected and often not yet ready for industry practice or broad market adoption. A rapidly evolving legislative framework for the European textile and clothing sector creates opportunities but also challenges and uncertainties for stakeholders wishing to adopt new technologies or other sustainable practices and business models.

The years until 2030 will be decisive to build the necessary knowledge base and technology infrastructure to be able to fully implement sustainable and circular business practices in textiles at large scale and to reap the benefits in the years thereafter to ensure the textile sectors contribution to the broader goals of the EU Green Deal and Fit for 55 strategy.

With a substantial and purpose-built research and innovation support programme Europe can ensure research, technology and industry leadership in this strategic sector of the economy, thereby creating many opportunities for European technologies, standards, best practices and business models that can be be adopted around the globe, especially in countries that currently account for the largest production and consumption impacts in this industry.

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Research Gaps and Needs for the Green Transition of the European Textile Ecosystem

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