WHITE PAPER

Technical Textiles for Space Applications

Industrial capabilities, innovation pathways and strategic outlook 2030–2060

CTNA Cluster Tecnologico Nazionale Aerospazio

CONFINDUSTRIA MODA FEDERAZIONE TESSILE E MODA

esa TECHNOLOGY BROKER Italy

White Paper - Technical Textiles for Space Applications

This document has been drafted by Confindustria Moda - TexClubTec within the framework of a dedicated Working Group launched by CTNA (Cluster Tecnologico Nazionale Aerospazio), in close collaboration with STAM Srl as ESA Technology Transfer Broker for Italy.

April 2026

Table of contents

1. Executive Summary

This opening chapter provides a synthesis of the document's key contents, outlining the strategic objectives of the initiative and the main results achieved. It offers a concise overview of the contributions and added value that the Italian technical textile industry can offer to address future space challenges and how the textile sector could benefit from spin-off of space technologies and solutions, the collaboration with ESA, and the future development outlook.

This White Paper has been developed within the framework of the activities of the Italian Aerospace Cluster (CTNA), which launched a dedicated Working Group coordinated by Confindustria Moda - TexClubTec and in synergy with the technology transfer activities of STAM Srl, as ESA Technology Transfer Broker for Italy, in close collaboration with the Italian Space Agency (ASI). The initiative aims to demonstrate how the Italian technical-textile ecosystem can meet the demanding functional, environmental, and operational requirements of space applications through coordinated cross-sector collaboration.

Technical textiles are emerging as a new frontier for space innovation, thanks to their adaptability, multifunctionality, and potential for sustainable design. Within this Working Group, CTNA, Confindustria Moda and the ESA Technology Broker for Italy jointly conducted a capability survey and a series of hands-on sessions and business-case workshops, including the Space2Tex event at ESA ESTEC on 17 October 2025, which confirmed the technological potential and industrial maturity of the Italian textile ecosystem, establishing a structured dialogue between space experts and national companies across the entire value chain, from fibers to multifunctional composites.

A **digital collaboration platform** is envisioned as the backbone of this initiative, enabling a **scalable and proactive ecosystem management** between space and textile innovators. This platform will act as a single interface between industry, academia, and institutional stakeholders, supporting the dissemination of opportunities, the alignment of standards, and the identification of synergies. Through functionalities such as a technology and asset marketplace, training modules on cross-cutting topics (e.g., ECSS compliance, Safe-and-Sustainable-by-Design - SSbD implementation, procurement guidance to access ESA, ASI, and Horizon Europe instruments), the platform will provide an operational environment for continuous interaction and project generation across both sectors.

The analysis identifies three synergistic **enabling technology clusters**:

- **Surface Engineering**, for example plasma activation, hybrid sol-gel coatings, and Diamond-Like Carbon (DLC) thin films offering hydrophobicity, flame retardancy, and resistance to atomic oxygen in Low Earth Orbit (LEO) conditions;
- **Innovative Materials and Processes**, for example shape-memory polymers, laser welding, and in-situ hardening materials enabling deployable or reconfigurable structures;

- **Smart Textiles and Bioplastics**, for example sensorised fabrics, EMI-shielding networks, antimicrobial coatings, and bio-based composites aligned with ESA's Green Agenda sustainability targets.

By combining these clusters, the textile sector can develop **self-monitoring, self-healing, and adaptive** material architectures designed for the extreme conditions of space, both as key components and subsystems of larger platforms and structures as well as wearable solutions both for intra- and extra-vehicular activities.

These preliminary activities allowed to define the main elements of a collaboration roadmap targeting 2030, with two possible phases for implementation:

- **Phase 1 (2026-2027):** establishing the cross-sectoral collaboration platform; launching proof of concepts and validation campaigns at reduced scale to support feasibility both in terms of spin-in and spin-off business cases (e.g. wearables, nonwoven MLI systems, deployable membranes); defining scale-up pathways and necessary milestones to move to in-space validation as well as demonstration of space tech in a real industrial environment; identifying funding opportunities, for example ESA Spark Funding, ESA GSTP, ASI programmes or Horizon Europe, to name a few.
- **Phase 2 (2028-2030):** accelerating qualification for technologies applied in spin-off projects, from space to non-space applications in the textile value chain; validation through shared testbeds for radiation, vacuum cycling, and dust in case of spin-in projects, creating capacity for advanced testing in textile testing facilities; develop pilot lines as Technology Infrastructures which may act as catalysts to engage SMEs and players in the textile value chain to address space challenges, in line with the broader EU strategy on advanced materials; disseminating results within the space and textile communities leveraging on the Digital Platform and the channels of CTNA and Confindustria Moda.

Ultimately, technical textiles could have the opportunity to become **core enablers** of Europe's next generation of space exploration and habitation systems. Their dual-use and cross-fertilisation potential represent a virtuous cycle of *spin-in* and *spin-off* innovation: technologies originally developed for terrestrial domains such as defence, mobility, and healthcare can be adapted for use in space, while space-qualified textiles and materials will, in turn, deliver tangible benefits to Earth-based sectors, including personal protective equipment (PPE), architecture, mobility, and sustainable design. By leveraging this bidirectional innovation flow, strengthened through the digital platform and a structured ecosystem governance, the Italian textile ecosystem can play a pivotal role in advancing both **space and non-space industries** through shared technologies, circular materials, and high-performance design paradigms.

2. Context and Strategic Framework

This chapter outlines the institutional and strategic framework of the initiative, launched by the Italian Aerospace Cluster (CTNA) and developed in partnership with Confindustria Moda - TexClubTec and STAM Srl, ESA Technology Transfer Broker for Italy. Together, these organisations have established a long-term collaboration to connect the Italian technical-textile industry with the space domain, providing a concrete example of cross-sector integration that contributes to ESA's objectives on sustainability, European autonomy, and supply-chain resilience.

The initiative builds on CTNA's coordination capacity in mapping national competences, TexClubTec's mandate to represent Italy's technical-textile industry, and STAM's facilitation role under ESA's Technology Transfer Programme, ensuring that ESA's material needs are translated into actionable industrial briefs and pilot projects. Together, they created an operational bridge between textile innovation and space requirements, positioning Italy as a frontrunner in the spin-in and spin-off of advanced materials and manufacturing processes.

The pathways consisted of key milestones that engaged the members of CTNA and textile stakeholders, as follows:

1. **October 2024 - Mapping and alignment.** Establishment of a CTNA working group to map technical capabilities and harmonise terminology between textile and space sectors.

2. **Spring 2025 - Activation of ESA Technology Broker support.** Formal involvement of STAM to translate ESA M&P requirements into industrial opportunities.

3. **June to October 2025 – Workshops and members survey.** During this period, a dedicated survey was launched within the CTNA Working Group to actively engage companies and collect feedback on their capabilities and needs. The initiative was complemented by a series of hands-on workshops hosted at Confindustria Moda headquarters and ESA ESTEC, organised in close collaboration with STAM in its role as ESA Technology Broker for Italy. In particular, the Space2Tex Workshop facilitated direct interactions between ESA experts and textile specialists, fostering alignment on testing procedures and qualification pathways.

4. **Late 2025 onward - Industrial outreach and continuous dialogue.** Participation in major events (e.g. Aerospace & Defence Meetings Turin) to engage primes and system integrators and foster joint developments and early proof-of-concept actions. A continuous dialogue between Confindustria Moda and CTNA will be maintained through regular progress meetings, leading up to the joint presentation of the White Paper and the definition of next-phase targets for the 2030 roadmap, in full synergy with the hands-on activities of the ESA Technology Broker for Italy.

This trajectory links national innovation capacity to Europe's broader goals for sustainability and technological autonomy. It complements ESA's Business Applications and Green Agenda initiatives, including projects such as *Greener Cotton* and *Sustainable Textiles for Space*, which promote greener materials, digital traceability, and circular value chains, in full synergy with the ongoing initiatives within the perimeter of the ESA Scale-Up programme and the activities of ASI in scientific and technological programmes. The collaboration now represents a key milestone for future dual-use developments under the 2030 roadmap and for the integration of Italian actors in European space value chains.

The strategic framework lays the foundation for a long-term collaboration platform connecting textile innovation, space technology, and industrial sustainability. Through CTNA's members engagement and Confindustria Moda's coordination and involvement, the initiative transforms isolated capabilities into an integrated ecosystem ready for spin-in and spin-off developments, in full synergy with the activities of the ESA Technology Broker and the Italian Space Agency.

3. Technical Requirements and Challenges

This chapter details the high-level functional, environmental, and operational requirements for space missions. It also highlights how the Italian textile ecosystem is adapting its design, testing, and qualification processes to meet these standards, enabling cross-fertilisation between terrestrial and space applications (spin-in projects), while defining specific challenges that space technologies could contribute to address (spin-off projects).

The development of space-qualified textiles demands compliance with an exceptionally stringent set of requirements that combine human safety, environmental compatibility, and mission reliability. While technical textiles are already engineered for harsh terrestrial environments-such as firefighting, industrial protection, and extreme outdoor use-the space context introduces unique constraints: vacuum exposure, atomic oxygen, radiation, extreme temperature cycles, and strict contamination control.

Go/no-go criteria, as emerged during the joint workshop at ESA ESTEC with TexClubTec and detailed in the PExTex and BACTeRMA projects, establish a hierarchy of essential and desirable properties that guide material qualification.

3.1 Core Functional Requirements

Core functional requirements define the essential properties necessary for space operations-non-flammability, antimicrobial performance, vacuum compatibility, mechanical integrity, and thermal management. Italian companies are progressively translating these criteria into material solutions that comply with ESA's ECSS standards while maintaining sustainability and production scalability.

Non-flammability

All fabrics intended for human environments in spacecraft or surface habitats must be intrinsically non-flammable. This implies the use of inherently flame-retardant fibers such as aramids, modacrylics, or engineered polyimides, or the adoption of multilayer structures incorporating fire-barrier membranes. ESA's flammability standards (ECSS-Q-ST-70-21C) tolerate no ignition or flame propagation under oxygen-enriched conditions. Italian companies have demonstrated compliance through PFAS-free coatings, silicone membranes, and ceramic nano-finishes capable of maintaining integrity under thermal load.

Antimicrobial and hygienic performance

In microgravity and closed habitats, laundering is infeasible; thus, textiles must prevent microbial growth and odour accumulation. The BACTeRMA experiment and ESA's "Keeping your underwear clean on the Moon" campaign (ESA, 2023) validated coatings and fibers with long-lasting antimicrobial activity without washing cycles. Italian partners offer plasma-activated surfaces, silver- and chitosan-based finishes, and hybrid coatings that combine hygiene and surface energy control-technologies initially developed for healthcare textiles and now adapted to space standards.

Vacuum compatibility and low outgassing

Outgassing can release volatile organics that condense on optical or thermal components, compromising spacecraft performance. Materials must pass space specific outgassing thresholds. Textiles for space must therefore rely on controlled polymerisation, minimal additives, and post-treatments such as vacuum baking, plasma cleaning, or silicone sealing. ESA's PExTex project demonstrated that surface finishes, adhesives, and inks often fail this requirement unless specifically reformulated. Italian research institutions such as Centrocot have begun establishing dedicated degassing test lines compatible with ECSS and ASTM standards.

Mechanical integrity and anti-punch resistance

Structural and deployable textiles must withstand micrometeoroid impact, mechanical stress, and handling loads without puncture or delamination. Layered composites combining aramid, UHMWPE, or basalt fabrics with elastomeric coatings have shown promise for impact absorption and containment (Workshop on Structural Textiles, 2025). These configurations must retain flexibility before deployment and maintain stiffness post-deployment-requirements that link directly to in-situ hardening or hybrid lamination technologies.

Thermal insulation and radiative control

Thermal management is critical both for human comfort and for spacecraft systems. ESA and Beyond Gravity studies on MLI (Multilayer Insulation) systems show how polymeric and metallised textile layers can achieve high reflectivity and low emissivity. Future textile-based solutions could integrate phase-change materials (PCM) and selective emissive coatings to adapt to varying temperature regimes, enabling adaptive thermal control. Such designs require precise control of layer spacing, surface roughness, and dust accumulation, as indicated in ESA's dust-proof materials calls (2024).

3.2 Environmental and Safety Requirements

Environmental and safety requirements cover resistance to radiation, atomic oxygen, UV exposure, and electrostatic discharge. Italy's expertise in coatings and surface engineering, including plasma activation and hybrid sol-gel deposition, offers sustainable and PFAS-free solutions aligned with ESA's Safe and Sustainable by Design principles.

Radiation, UV and Atomic Oxyen resistance

Textiles used externally or in lunar surface operations must resist ionising radiation, UV exposure**, Atomic Oxygen erosion**, and thermal shock. Polymers degrade through chain scission and crosslinking, leading to embrittlement and colour change. ESA's PExTex and Next Generation of Materials for Space Applications studies emphasise the importance of stabilisers, hybrid inorganic coatings, and reflective pigments to extend operational lifetimes. External textiles and coatings operating in low-Earth orbit or on exposed spacecraft surfaces must withstand continuous erosion by atomic oxygen (AO). This highly reactive species, formed by photodissociation of molecular oxygen, can oxidise and erode polymer surfaces, reducing mechanical integrity and increasing emissivity. Protective coatings-such as silicon oxides, DLC films, or hybrid sol-gels-are therefore essential to preserve functionality. Italian expertise in plasma coatings and inorganic surface layers provides a strong technological base for AO-resistant finishes aligned with ESA's Materials and Processes specifications (ESA PExTex, 2023). The Italian textile industry's experience with outdoor and military applications provides a solid foundation for developing radiation-tolerant formulations.

Anti-static and EMI shielding

Electrostatic charge accumulation in dry or vacuum environments can lead to discharge and damage sensitive electronics. Conductive yarns, carbon-loaded coatings, or metalised fibers can provide controlled surface resistivity. These solutions must maintain electrical continuity while avoiding sharp edges or conductive dust. EMI shielding is equally critical in smart wearables and deployable structures housing sensors or electronic systems; conductive textiles can act as lightweight Faraday cages or grounding networks.

Fire safety in oxygen-rich environments

Beyond non-flammability, ESA defines detailed ignition and propagation test protocols for confined atmospheres. Italian research centers have adapted fire testing to oxygen-enriched conditions, using small-scale chambers to measure flame spread and heat release rate. Combined with self-extinguishing fiber blends, these tests ensure compliance at both material and system level.

3.3 Functional and Operational Requirements

Beyond material resilience, textiles for space must be operationally reliable-flexible, foldable, and capable of integrating sensors or self-healing mechanisms. Italian R&D centers are pioneering adaptive membranes and conductive fabrics enabling autonomous monitoring and maintenance, essential for long-duration missions.

Flexibility and foldability

Deployable and wearable textiles must remain highly flexible for compact stowage, yet able to recover shape or harden upon deployment. The workshop breakout session on structural textiles highlighted solutions such as one-axis foldable geometries, welded seams for airtightness, and in-situ hardening polymers that transition from soft to rigid when exposed to temperature, pressure, or UV triggers. Such functionalities are vital for inflatables, shelters, or shields that must combine low volume with large surface coverage.

Smart sensing and integration

ESA's vision for intelligent materials extends to textiles capable of real-time self-diagnosis. Integrated fiber sensors, conductive pathways, and flexible electronics can monitor strain, temperature, humidity, and even micro-perforations. For example, Italian developments in conductive nanofibers and textile-integrated circuits (TexClubTec, 2025) demonstrate how sensing can be distributed over large areas, reducing wiring complexity. This is essential for adaptive suits, inflatable habitats, or large deployable structures where visual inspection is impossible.

Durability and reparability

Long-duration missions demand textiles that can self-heal or be repaired with minimal resources. Research from the Politecnico di Milano and ESA's Towards Safer Space Suits with Self-Healing Materials (2021) shows promising polymers capable of re-bonding under heat or light stimuli, restoring up to 80% of mechanical strength. Coupled with modular garment design, this ensures longer service life and reduced waste, aligning with the ESA Green Agenda and sustainability goals.

3.4 Testing and Qualification Challenges

Qualification of textile-based materials for space remains complex due to limited harmonisation across ECSS standards. Italian testing centers are collaborating to establish shared testbeds for combined radiation, vacuum, and thermal exposure, accelerating the transition from TRL 4 to TRL 6-7.

Validating textile materials for space applications remains complex because traditional space standards were developed for metals and composites. ESA's Materials and Processes (M&P) division has been progressively expanding ECSS standards to include flexible substrates and coatings, yet test protocols for textiles remain non-harmonised across Europe. Critical gaps include long-duration exposure to atomic oxygen, radiation synergies, microgravity effects on material fatigue, and combined environment cycling.

Environmental exposure testing must include combined AO-UV-thermal cycling to simulate degradation under low-Earth orbit conditions. National research centers are developing test capabilities for AO erosion, in cooperation with ESA M&P, to validate surface treatments and assess long-term stability of functional coatings. Italian testing centers are collaborating to establish dedicated testbeds for textile materials, integrating vacuum chambers, UV-thermal cycles, and radiation sources. This initiative aims to shorten the qualification loop and enable SMEs to reach TRL 6-7 without prohibitive costs.

3.5 Space-to-Earth Technology Transfer Requirements (Spin-off)

As anticipated, beyond the adaptation of textile technologies to space applications, an equally strategic dimension concerns the reverse pathway, **the transfer of space-originated materials, processes, and methodologies to the textile and advanced-manufacturing sectors.** Under the coordination of CTNA and Confindustria Moda - TexClubTec, and in synergy with STAM Srl, ESA Technology Broker for Italy, a first set of criteria has been identified to enable this *spin-off* direction and ensure that future ESA and ASI developments can generate tangible industrial benefits.

Space technologies intended for transfer to terrestrial textile processes should demonstrate **process scalability**, **material compatibility**, and **sustainability compliance** with existing industrial and regulatory frameworks. This includes the ability to adapt to **continuous roll-to-roll production**, ensure **non-toxicity and PFAS-free formulations**, and provide **digital traceability data** consistent with Safe and Sustainable by Design (SSbD) principles and the Digital Product Passport approach promoted by Confindustria Moda.

Equally, **data transparency and qualification traceability** are essential. Space technologies should be accompanied by open or standardised datasets covering composition, outgassing, and radiation resistance, in formats interoperable with both **ECSS** and textile certification standards. **Economic feasibility**-including the availability of pilot partners, proven manufacturability at TRL ≥ 6, and a clear cost-benefit profile-will further determine their transfer potential.

In summary, **the overall set of requirements converges toward multi-functional, sustainable textile systems that combine safety, environmental compatibility, and intelligence.** The **challenges are therefore dual**: on one side, enabling the **spin-in** adaptation of textile technologies to space standards; on the other, ensuring the **spin-off** integration of space-born innovations into terrestrial manufacturing and circular-economy frameworks. Italy's textile ecosystem is uniquely positioned to address both directions through coordinated R&D, industrial partnerships, and European collaboration.

4. Italian Industrial Capabilities

Italy's technical-textile industry forms a complete, vertically integrated value chain capable of supporting both industrial and space-grade production. This chapter outlines the structure, technological strengths, and innovation capacity that make Italy a key actor in Europe's textile-space integration strategy.

4.1 Value Chain and System Integration

The Italian supply chain encompasses raw-material producers, specialised finishers, machinery and process innovators, testing laboratories, and end-product integrators. This structure allows for fast iteration between design, prototyping, and validation**,** a fundamental advantage when adapting materials to ESA requirements.

Italian textile districts host world-leading companies in protective clothing, filtration, composite reinforcement, membranes, and smart fabrics. Their historical expertise in high-performance technical textiles-developed for defense, automotive, and industrial protection-naturally extends to space applications. The ability to combine small-series flexibility with industrial repeatability is central to ESA's supply philosophy, as space qualification increasingly seeks cross-sector manufacturing readiness.

4.2 Technological Strengths

Surface Engineering

Italian firms have established world-class know-how in plasma activation, sol-gel coatings, and Diamond-Like Carbon (DLC) deposition on flexible substrates. These processes enable controlled surface energy, hydrophobicity, flame retardancy, and adhesion without relying on PFAS or halogenated compounds-aligning with Safe and Sustainable by Design (SSbD) principles (European Commission, 2024). Roll-to-roll vacuum systems, already used in packaging and optics, have been adapted for textile finishing, offering the repeatability and traceability required for space qualification.

Advanced Finishing and Functionalisation

The sector has pioneered functional coatings that combine fire retardancy, UV stability, and antimicrobial behaviour while maintaining mechanical flexibility. Several Italian producers already supply ISO 9100-qualified space components, including thermal control blankets, filtration layers, and protection systems. Collaboration with Beyond Gravity (former RUAG) and participation in ESA's PExTex study demonstrated that industrial coatings and membranes from Italy can meet the cleanliness and outgassing criteria for orbital and lunar use.

Testing and Qualification

Research and testing centers have developed dedicated testing capabilities for flammability, outgassing, degassing, mechanical performance, and vacuum exposure. These centers act as the interface between industry and ESA/ASI standards, enabling SMEs to test materials in conditions representative of spacecraft cabins or lunar surface operations.

4.3 Innovation and Digitalisation

The Italian textile industry has also embraced digital traceability and life-cycle monitoring, essential for both sustainability and space material certification. Through the TexClubTec Traceability Initiative, QR-based data systems are used to document fiber origin, chemical processes, and finishing parameters-data that can be directly aligned with ESA's material databases and ECSS documentation. Such systems allow for transparent end-to-end traceability, fulfilling both environmental and mission assurance needs.

4.4 Strategic Positioning

Overall, the Italian textile ecosystem demonstrates a distinctive combination of technological excellence, manufacturing flexibility, and innovation capacity that makes it a strategic contributor to Europe's space and advanced-materials landscape, through:

- **A mature technological base ready for cross-sector qualification (TRL 4-6).** Decades of experience in technical and performance textiles have produced an industrial fabric capable of meeting the stringent functional and safety requirements of space applications. Companies across the national value chain can already supply components compatible with ECSS standards, providing a solid foundation for rapid progression toward TRL 7 and beyond.

- **Deep expertise in surface engineering and functional finishing adaptable to space use.** Italy leads in plasma treatments, hybrid sol-gel coatings, thin-film deposition, and advanced laminates that deliver flame retardancy, antimicrobial protection, and environmental resistance without PFAS or halogenated compounds. These capabilities are directly transferable to the development of smart, self-healing, and radiation-resistant materials required for future exploration and orbital infrastructure.
- **An integrated network of research, production, and certification actors.** The close interconnection between industrial clusters, academic centers, and accredited laboratories enables rapid prototyping, iterative testing, and the harmonisation of data with European qualification standards. This collaborative infrastructure supports both the spin-in adaptation of textile technologies to space and the spin-off application of space innovations to terrestrial manufacturing.
- **A systemic commitment to sustainability and circular-economy innovation.** Italian textile producers are embedding Safe and Sustainable by Design (SSbD) approaches, digital traceability, and life-cycle monitoring into production workflows. These efforts align with ESA's Green Agenda targets, aiming to maximise the use of space for environmental objectives, reduce the ecological footprint of materials and processes, and foster cross-sector awareness of sustainability as a design parameter rather than a post-production constraint.

By combining technological maturity, multidisciplinary integration, and environmental responsibility, **Italy's textile industry is evolving from a supplier of specialised materials into a strategic enabler of sustainable and intelligent systems for both space and Earth applications.**

5. Enabling Technologies and Innovation Pathways

Italy's progress toward the development of next-generation technical textiles for space is driven by a dynamic exchange between terrestrial innovation and space research. The three main technological pillars**, surface engineering, innovative materials and processes, and smart textiles and bio-based materials,** operate as bidirectional pathways for technology transfer: enabling the **spin-in** of textile capabilities into space missions and, conversely, the **spin-off** of space-borne technologies into advanced textile manufacturing on Earth. Together, they outline a continuous innovation cycle where sustainability, multifunctionality, and digitalisation converge to create materials and processes that benefit both domains.

5.1 Surface Engineering

Surface engineering forms the first barrier between textile materials and the extreme conditions of space. Italian companies lead in applying plasma, laser, and thin-film deposition to textiles, offering non-chemical routes to functionality, while needing solutions which space can enable.

Spin-in perspective. Plasma functionalisation modifies surface polarity and adhesion, enabling water repellency, dye affinity, or compatibility with silicones and fluorine-free coatings. Atmospheric and low-pressure plasma technologies have been industrialised for continuous textile lines, providing reproducible, solvent-free modification. DLC coatings-ultrathin carbon films deposited under vacuum-improve abrasion, wear, and flame resistance while maintaining flexibility. DLC also enhances surface cleanliness, reducing outgassing and dust accumulation-crucial for lunar operations (*ESA dust-proof materials, 2024*). Sol-gel and hybrid coatings enable multifunctional surfaces combining thermal reflectivity, antimicrobial action, and self-cleaning. These coatings, validated in ESA's *PExTex* and *BACTeRMA* projects, can be applied to both woven and nonwoven structures.

Spin-off perspective. The same plasma and hybrid-coating technologies initially developed for spacecraft protection are now supporting the creation of low-impact, PFAS-free finishing processes for industrial textiles, promoting longer material lifetime and reduced chemical use. This bidirectional transfer demonstrates how sustainable finishing techniques and advanced surface treatments can strengthen both space and terrestrial material value chains.

5.2 Innovative Materials and Processes

New materials and processes extend textile functionality beyond traditional limits. Shape-memory polymers and in-situ hardening resins allow deployable structures; laser welding offers clean, adhesive-free sealing; and additive manufacturing enables graded, lightweight architectures for inflatables and protective layers.

Spin-in perspective. Shape-memory and adaptive polymers can alter stiffness or geometry under thermal or electrical stimuli, providing deployable structures with reconfigurable behaviour. Italian R&D centers are developing polymer matrices capable of in-situ hardening, a key mechanism for inflatable habitats or morphing skins. Laser cutting and welding enable clean, non-contaminating processing compatible with space contamination-control requirements. Laser joining can seal multi-layer laminates, ensuring airtight seams without adhesives that could outgas in vacuum. The integration of additive techniques allows for graded structures, integrated channels, and hybrid reinforcement of complex geometries. 4D printing adds time-dependent behaviour, essential for self-deploying systems. Italian SMEs specialised in 3D weaving and knitted composites are already transferring know-how from sports and automotive sectors to space demonstrators. Combining carbon, aramid, and biopolymer fibers in hybrid fabrics provides tunable stiffness, damping, and environmental resistance, ideal for secondary structures, deployable systems, and thermal-protection layers.

Spin-off perspective. These same structural and joining innovations can enhance terrestrial textile production, particularly in lightweight composites, protective architecture, and circular design. Processes validated for space, such as laser joining and shape-memory polymer hardening, can inspire recyclable laminates, modular membranes, or adaptable fabrics for industrial, civil, and mobility applications. This reinforces the reciprocal nature of innovation, where space qualification feeds industrial competitiveness and vice versa.

5.3 Smart Textiles and Bioplastics

Smart textiles merge electronics and materials, integrating distributed sensing networks for temperature, strain, and biochemical monitoring. Bio-based polymers (PLA, PHB, cellulose derivatives) and self-healing coatings contribute to ESA's *Green Agenda* goals. Nanofiber structures offer dust-mitigation and radiation-shielding potential.

Spin-in perspective. Conductive fibers, metallic filaments, and printed circuits can measure temperature, strain, and biochemical markers. The Space Agencies vision for intelligent materials aligns with TexClubTec developments in e-textiles that self-monitor deformation and ageing. This is particularly relevant for adaptive suits and deployable structures, where embedded sensing enables predictive maintenance and safety assurance.

Spin-off perspective. The same sensorisation, monitoring, and data-handling technologies developed for spacecraft environments can support industrial automation, health monitoring, and protective equipment on Earth. Similarly, bioplastic membranes and self-healing coatings from space projects can be re-engineered for sustainable fashion, filtration, and smart home applications, demonstrating how knowledge gained through space R&D directly benefits the broader textile value chain.

5.4 Innovation Pathways and TRL Progression

Each of these clusters contributes to a staged innovation pathway aligned with ESA's Technology Readiness Levels (TRLs):

- TRL 3-5: laboratory validation of coatings, plasma treatments, and sensor integration;
- TRL 5-6: system integration and environmental testing with ESA M&P;
- TRL 6-8: demonstration in ESA/ASI pilot missions or testbeds for wearables, MLI systems, or deployable membranes.

In parallel, spin-off developments leverage the same validation chain in reverse, translating qualified materials and processes into scalable, sustainable textile production systems on Earth. The synergy between the three clusters, surface, structural, and smart materials and components, forms a comprehensive roadmap for transforming terrestrial textile expertise into certified space materials and, reciprocally, reintroducing space-qualified solutions into industrial manufacturing. This approach reflects Space Agencies principle of cross-sector innovation and strengthens Italy's position within the European space-materials ecosystem.

By coupling spin-in and spin-off innovation, Italy's technical-textile sector is positioned as a key contributor to Europe's goals for sustainable autonomy, enabling new materials for space missions while translating space technologies into tangible industrial and societal benefits.

6. Cross-Sector Synergies and Dual-Use Opportunities

Technical textiles offer a unique interface between terrestrial innovation and space requirements. Their intrinsic versatility, scalability, and capacity for multi-functionality make them strategic enablers of both wearable systems and structural or deployable systems in future space missions. **At the same time, many of the materials, processes, and data-driven methodologies validated under space programmes can be re-engineered to strengthen terrestrial textile applications, closing the loop between spin-in and spin-off innovation.** The Italian industrial base, as mapped by TexClubTec and CTNA, already demonstrates strong potential to adapt proven technologies, originally developed for personal protection, mobility, and energy sectors, to space-qualified use, and to re-introduce space-tested solutions into industrial contexts.

This section is divided into two parts: **Wearable Systems and Human-Centric Applications** and **Structural Textiles and Deployable Systems**, each illustrating how cross-sector synergies operate in both directions.

6.1 Wearable Systems and Human-Centric Applications

ESA's current efforts in projects, such as the PExTex and BACTeRMA projects, highlight a growing demand for textiles that ensure safety, hygiene, comfort, and sensing in confined, high-risk environments. Italian textile innovation, traditionally centered on advanced protection and smart functionality, offers direct relevance to these missions.

Smart sensing integration

Recent developments in sensorised fabrics allow distributed measurement of strain, temperature, humidity, and biochemical parameters. Seamless integration of such sensors into textiles eliminates fragile junctions and enables continuous physiological monitoring of astronauts, improving mission safety. ESA studies on antimicrobial and washable-free materials for spacesuit inner linings (ESA 2023; Keeping Your Underwear Clean on the Moon) confirm the feasibility of comfort-oriented, low-maintenance wearables. Italian companies have already demonstrated textile platforms capable of embedding flexible electrodes and conductive paths, compatible with vacuum-resistant coatings and low-outgassing adhesives.

Functional performance

Wearables must combine non-flammability, antimicrobial behaviour, flexibility, and resistance to abrasion and dust infiltration. Silicone or fluorine-free coatings, plasma-treated aramid fabrics, and multilayer knits with silver-based antimicrobial functions have all shown compatibility with space go/no-go criteria.

In this context, smart textiles bridge health monitoring, environmental protection, and mission efficiency, turning garments into multi-functional nodes of the life-support system. Their modularity and reparability, enhanced by self-healing polymers (Politecnico di Milano 2023; Towards Safer Space Suits with Self-Healing Materials), contribute to long-duration sustainability and reduced logistics loads.

Cross-sectoral and dual-use relevance

Many of these technologies originate from personal protective equipment, sportswear, and medical textiles. Their adaptation to space, through stricter flammability, vacuum, and radiation validation, creates a bidirectional innovation channel where terrestrial know-how enables human-centered space systems and, conversely, space validation enhances performance, durability, and digital integration in terrestrial markets. Sensorised garments and antimicrobial coatings tested in orbit can improve infection control in hospitals, predictive health monitoring in sports and rehabilitation, and safety equipment for first responders. Similarly, lightweight, thermally adaptive layers designed for EVA suits inspire new generations of sustainable fashion and industrial apparel that merge comfort with protection. This cross-sector feedback loop reinforces the role of the textile industry as a provider of enabling technologies for both space life-support systems and human-centric innovation on Earth.

6.2 Structural Textiles and Deployable Systems

Beyond personal wearables, textiles play a growing structural role in deployable habitats, shields, and inflatable structures, fields where Italy holds notable expertise through collaborations with ESA, ASI and academic research groups.

Functional requirements

Workshop discussions with ESA identified the following high-level requirements for space-borne structural textiles:

- Full containment of atmosphere (airtight membranes with no perforations);
- Thermal insulation and anti-punch resistance to protect against micrometeoroids or mechanical stress;
- Anti-static and antimicrobial properties to prevent contamination and electrostatic discharge;
- Flexibility and foldability, allowing large deployable surfaces with compact stowage;
- Fire resistance and low off-gassing behaviour to meet cabin safety and cleanliness standards.

Material architecture

The proposed pathway combines an internal functional layer, responsible for insulation, structural integrity, and anti-punch protection, with an external shielding layer that provides dust, radiation, or micrometeoroid defence. Post-processing may involve welding or lamination techniques to ensure airtight joints, and in-situ hardening mechanisms that allow flexible materials to become rigid once deployed. Controlled single-axis foldability simplifies packaging and ensures predictable deployment, consistent with ESA studies on inflatable and dust-proof materials (ESA 2024).

Integration with smart systems

The convergence of smart sensing and structural textiles opens new frontiers for autonomous monitoring of strain, fatigue, and micro-leakage. Embedding flexible sensors and conductive networks within the textile layers enables early detection of mechanical degradation or micrometeoroid impact. These features directly support ESA's sustainability and safety objectives by extending component lifetime and enabling predictive maintenance of space habitats.

Cross-sectoral and dual-use relevance

Technologies developed for space deployable systems have clear terrestrial applications in civil protection, temporary shelters, high-performance architecture, and lightweight transport systems. Inflatable and foldable membrane structures originally designed for lunar or orbital habitats can evolve into emergency modules, mobile hospitals, or modular greenhouses operating in remote environments. Industrial processes used for automotive airbags, composite reinforcement, and architectural membranes can, with suitable material qualification and outgassing control, supply components for space systems- while space-validated materials enhance reliability and longevity in Earth-based engineering. This two-way exchange exemplifies how the textile sector bridges space, construction, and mobility, transforming lessons learned from extreme environments into sustainable structural solutions for everyday life.

Together, wearable and structural textile systems illustrate the full potential of the Italian technical-textile industry as a cross-sector enabler. **Their convergence defines a truly cross-sectoral innovation ecosystem, where material science, process engineering, and embedded intelligence circulate seamlessly between industrial and space domains.** Textiles thus emerge as a cornerstone for both human-centered and structural solutions in future ESA and ASI programmes, while simultaneously advancing terrestrial industries in line with Europe's sustainability and digital-transition goals. These capabilities position Italy to contribute significantly to **Europe's strategic autonomy in sustainable, intelligent, and circular space materials**.

7. Gap Analysis and Future Needs

This chapter identifies the main technical, procedural, and strategic gaps that must be addressed to ensure the full maturation of textile-based materials for space applications and their integration into European qualification frameworks. While Italy has demonstrated significant progress in surface engineering, material innovation, and testing capabilities, several structural barriers still limit the transition from laboratory-scale validation to certified, flight-ready systems. These same barriers also affect the reverse path, namely, the spin-off transfer of space-derived materials and processes to terrestrial textile manufacturing, making the closure of these gaps a shared prerequisite for both directions of innovation. The identified gaps fall into four main categories: Standardisation, Endurance and Long-Term Validation, Demonstration and System-Level Integration, and Dissemination & Funding Access.

7.1 Standardisation

The first and most pressing gap concerns **standardisation and harmonisation of testing and qualification procedures for flexible materials across different regulatory frameworks**. Current **ESA and ECSS standards** were primarily developed for metals and rigid composites, leaving limited guidance for parameters specific to textiles-such as porosity, weave geometry, coating adhesion, multilayer coupling, and degradation mechanisms under combined environmental stress. This lack of harmonisation generates inconsistencies across laboratories and hinders comparability of results, increasing the time and cost of qualification. Beyond the ECSS environment, existing industrial standards such as ISO, ASTM, and REACH provide only partial coverage of textile-specific tests relevant to space contexts, while European frameworks on Safe and Sustainable by Design (SSbD) introduce additional requirements on chemical safety, traceability, and circularity.

The challenge is therefore to establish a unified cross-standard reference that bridges space testing (ESA/ECSS) with terrestrial industrial and environmental regulations (ISO, REACH, SSbD), enabling the qualification of materials for both domains. Shared interpretation of ECSS documentation, as well as harmonised degassing, vacuum, radiation, and atomic-oxygen test protocols, are essential prerequisites for any future qualification framework. Equally important is the alignment with textile-specific industrial protocols, such as flammability and cleanliness tests, adhesion durability, and chemical emission control, ensuring that results are comparable and transferable between space and manufacturing laboratories. A related gap concerns digital standardisation of materials data: information is often stored in heterogeneous formats, limiting traceability and integration within ESA's Materials and Processes (M&P) databases.

To enable interoperability between space and non-space actors, datasets should follow **common digital structures (metadata, versioning, material genealogy) compatible with ECSS, ISO 9001/14001, and digital product passport principles.** The adoption of common digital formats, metadata structures, and secure data-exchange protocols would allow SMEs to contribute efficiently to material databases and facilitate cross-sector use of textile data.

From the identified challenges, it becomes evident that there is a need to take action and adopt a systematic approach to standardisation, **developing textile-specific procedures (flammability, outgassing, cleanliness, adhesion testing) that align simultaneously with ECSS and ISO requirements and with Safe and Sustainable by Design (SSbD) principles.** Such alignment would directly support both spin-in qualification of textile innovations for space and spin-off certification of space-derived materials for terrestrial manufacturing.

7.2 Endurance and Long-Term Validation

The second major gap relates to endurance evidence and long-term performance validation. Although single-environment tests (e.g. AO exposure or UV ageing) are available, combined-environment data reproducing actual mission conditions remain limited. Textile architectures, by nature, exhibit complex degradation behaviours where fiber fatigue, coating delamination, and polymer oxidation interact synergistically.

Without statistically robust, long-duration datasets, it is difficult to predict the mechanical and functional stability of textile composites across different mission profiles. Therefore, the development of **integrated environmental test campaigns combining AO-UV-thermal-radiation exposure cycles** is essential to achieve TRL 6-7 maturity. These campaigns should be conducted under ESA supervision, building on methodologies pioneered in the **PExTex** and **BACTeRMA** projects (*ESA Nebula, 2022-2023*), and leveraging textile testing facilities**.** Such validation efforts would provide the quantitative evidence required for both

space qualification (spin-in) and **industrial durability certification (spin-off)**, positioning Italy as a European reference for endurance assessment of flexible, multifunctional materials.

7.3 Demonstration and System-Level Integration

The third gap concerns the limited number of **TRL6-8 system-level demonstrators** available for both wearable and structural textile applications. While many coatings and materials have achieved laboratory validation, few have been integrated into operational subsystems such as inflatables, thermal blankets, or protective garments. This absence of demonstrators slows industrial adoption and limits the visibility of textile innovation within ESA and ASI programmes. Demonstration is a critical step in bridging the gap between research and qualification, it provides evidence of scalability, manufacturability, and compliance under representative environmental conditions. Future developments should therefore prioritise **prototype integration campaigns**, clustering SMEs and research centers into targeted demonstrator consortia.

Priority areas include, for example:

- **Wearable systems**, to validate antimicrobial, flame-retardant, and sensing functionalities in confined or microgravity environments.
- **Structural and deployable membranes**, integrating airtightness, anti-puncture resistance, and dust-mitigation features.
- **Thermal protection and insulation layers**, combining multi-layer insulation (MLI) and adaptive coatings for variable emissivity.

For the **spin-in** route, such demonstrators accelerate readiness toward flight qualification; for the **spin-off** route, they serve as industrial showcases, allowing space-validated materials to prove their scalability in terrestrial markets such as emergency shelters, smart PPE, or energy-efficient architecture.

7.4 Dissemination, Training, and Funding Access

The fourth gap involves **dissemination of results, capacity-building, and access to funding mechanisms**. Despite the progress achieved, textile SMEs lack the know-how to navigate ESA and ASI procurement processes, prepare ECSS-compliant documentation, or identify appropriate financial instruments.

A **structured and proactive ecosystem management digital platform to support interactions between space and textile innovators, acting as dissemination and capacity building platform**, would ensure a single interface between industry, academia, and institutional stakeholders, including large primes. The platform will also coordinate capability mapping across the textile and space sectors, maintain a dynamic marketplace of materials and testing competences, and facilitate joint participation in ASI, ESA, and Horizon Europe programmes. This operational model reinforces collaboration continuity and ensures that industrial capabilities are connected with research infrastructures and funding opportunities in real time.

This platform could provide:

- **Training modules** on ECSS compliance, digital material certification, and SSbD implementation;
- **Knowledge-sharing workshops** and webinars to align the textile sector with space requirements and space technology providers with textile specific processes and constraints;
- **A continuously updated marketplace of technologies, materials, testing competences, and assets originating from both the space and textile domains,** enabling visibility and matchmaking for innovation opportunities, showcasing ready-to-transfer solutions, prototypes, and laboratory capabilities available for technology brokerage and industrial adoption. It will also support the identification of needs and offers related to ESA, ASI, and industrial primes, facilitating cross-sector valorisation and co-development initiatives;
- **Procurement and Funding guidance** to help companies access ESA, ASI and relevant funding and procurement practices in the space sector, taking advantage of the ESA Spark Funding instrument made available by the ESA Technology Broker or relevant *Horizon Europe* calls to support technology transfer projects;
- A **library of best practices and success stories** documenting dual-use pathways and lessons learned from spin-in and spin-off collaborations.

This combination of training, matchmaking, and brokerage functions will transform the platform into a living ecosystem for knowledge valorisation-where industrial actors can identify, adapt, and co-develop space and non-space technologies for dual-use applications.

For **spin-in** innovation, the digital platform strengthens technical readiness and compliance; for **spin-off** exploitation, it fosters visibility, matchmaking, and investor confidence, establishing a self-sustaining environment for cross-sector knowledge valorisation.

8. Roadmap and Strategic Recommendations

This chapter identifies possible short- and medium-term objectives, performance indicators, and strategic actions designed to support the progressive qualification of textile materials for space applications or identify space solutions to textile challenges. The roadmap operationalises the strategic vision presented in the Executive Summary by translating the outcomes of CTNA and Confindustria Moda joint activities into a structured plan for implementation. The strategy follows a two-phase approach corresponding to the spin-in and spin-off innovation flows described throughout this White Paper.

8.1 Phase 1 (2026-2027): Proof of Concept and Validation

The first implementation stage (2025-2027) will focus on consolidating the organisational and technical foundations required to integrate textile innovation into the space sector and viceversa.
Under CTNA's coordination and Confindustria Moda - TexClubTec's industrial guidance, and with technical facilitation by STAM Srl as ESA Technology Broker for Italy in collaboration with ASI, this phase will establish the cross-sectoral collaboration platform connecting Italian textile SMEs, research centers, and space companies. The platform will coordinate **capability mapping**, maintain a **marketplace of materials and testing competences**, and facilitate joint participation in future **ASI, ESA, and Horizon Europe** programmes.

During this period, **three tech transfer proof of concepts** will be defined, targeting:

- Human-centric applications (e.g. antimicrobial, fire-retardant, and sensing textiles);
- Lightweight, thermally stable materials compliant with outgassing and cleanliness requirements for indoor environments;
- Deployable membranes, evaluating dust-mitigation and foldability performance under combined environmental stress.

An **ECSS alignment guide for textiles** will be investigated to interpret existing standards for flexible materials and adapt them to textile testing, certification, and documentation needs. This will support SMEs and laboratories in meeting space M&P criteria. In parallel, **Safe and Sustainable by Design (SSbD)** approaches, **PFAS-free roadmaps**, and **digital traceability mechanisms** will be embedded in pilot manufacturing lines, ensuring compliance with the European Green Deal, the ESA *Green Agenda*, and national sustainability policies.

Funding opportunities will consider ESA Spark Funding or GSTP or EU Funding instruments, facilitating proof-of-concept demonstrators and industrial feasibility studies. The objective of this first phase is to demonstrate technical readiness, build the first cross-sector supply chains, and establish a clear regulatory and data framework for textile qualification.

8.2 Phase 2 (2028-2031): Demonstration and Qualification

The medium-term horizon (2028-2031) will focus on transitioning from validation to **system-level demonstration and qualification** of textile subsystems. Selected materials and components, previously validated under CTNA and Confindustria Moda coordination, will be qualified to **TRL6-7**, working in close partnership with system integrators and space agencies. Demonstrators will include both **spin-in use cases** (integration of space-grade materials in industrial applications) and **spin-off pathways** (adapting terrestrial technologies for orbital or planetary missions).

In this period, **shared testbeds** for radiation, vacuum cycling, and dust exposure will be consolidated within national laboratories, creating the capacity for advanced testing of spin-in projects and real-environment validation for spin-off developments. At the same time, **manufacturing demonstrators**, including roll-to-roll deposition, plasma treatment, and laser joining systems to name a few, will be deployed to support on-site testing, scalability analysis, and rapid prototyping. These demonstrators will accelerate the transition from lab-scale validation to industrial production and enhance Italy's visibility within the European innovation landscape.

Finally, a structured **dissemination and outreach programme** will be implemented toward primes, agencies and sectoral associations through CTNA and Confindustria Moda. This will ensure the visibility of Italian competences and promote the inclusion of textiles as enabling technologies within ESA's procurement and R&D strategies.

9. Long-Term Outlook 2031–2060: Technical Textiles in the future Space Economy

The completion of the short- and medium-term actions described in the previous chapter will establish the technical, organisational and regulatory foundations necessary for textile-based materials to enter the space domain and, in parallel, for space-derived technologies to be transferred to the textile value chain. Once these structures, demonstrators and testing infrastructures are in place, the ecosystem will be positioned to contribute to a broader, long-term transformation of materials and manufacturing systems.

Looking beyond 2031, the evolution of the global space economy will progressively expand the role of technical textiles in exploration, in-orbit production and sustainable off-world infrastructures. The 2031–2060 horizon can be interpreted through three major evolutionary phases, each characterised by different mission contexts, material requirements and industrial opportunities for Italy's technical-textile sector.

9.1 Early Off-World Operations and Surface Systems (2031–2045 |

The first phase begins once the initial wave of terrestrial-to-space demonstrators, material qualification pathways and cross-sector testbeds reach maturity around 2031. In the decade that follows, space operations will gradually transition from intermittent missions to more continuous and structured activities. These include increased surface operations in harsh environments, the deployment of early research infrastructures and the consolidation of logistics workflows supporting long-duration habitation and scientific work.

This evolution generates a growing demand for technical textiles that can withstand abrasive dust, extreme temperature cycles, fluctuations in radiation exposure and mechanical stress during deployment. Materials must combine insulation, abrasion resistance, low outgassing, structural flexibility and durability under repeated folding or packing. Surface textiles, both wearable and structural, will require hybrid coatings, controlled emissivity, advanced membrane architectures and polymer formulations capable of preserving performance in low-pressure or vacuum environments.

Wearable systems will also become progressively more sophisticated. Garments will need to maintain hygiene, antimicrobial performance and comfort without regular maintenance, while integrating sensing capabilities for physiological and environmental monitoring. The developments initiated during the 2025–2031 period, including antimicrobial treatments, fire-resistant textiles and sensorised fabrics, will be further adapted for long-duration use and integrated into larger life-support systems.

Structural textiles will support early surface infrastructures through deployable membranes, insulation layers, protective shielding and adaptive skins capable of modulating stiffness or thermal behaviour. These materials will benefit directly from the maturation of roll-to-roll finishing systems, plasma processes and laser joining technologies that will be operational in Italy by 2031.

9.2 Expansion of In-Situ Construction and Orbital Manufacturing (2045–2055)

The second phase corresponds to increasing reliance on autonomous construction systems and the expansion of in-orbit manufacturing from experimental modules to industrially meaningful production. During this period, space systems will depend on materials that are extremely lightweight, adaptive, and compatible with automated assembly and additive manufacturing processes.

On off-world surfaces, textile-based materials will be integrated into pressurised volumes, protective enclosures and hybrid structures fabricated using in-situ resources combined with imported high-performance fibres or membranes. In-situ hardening polymers, adaptive laminates and graded textile composites will become essential components of autonomous construction workflows.

In orbit, microgravity will be fully exploited as a manufacturing environment for advanced materials. The absence of convection and sedimentation enables unique blending and self-organisation behaviours, resulting in ultra-homogeneous composites, high-purity polymeric films and functional membranes with enhanced structural order. These materials have the potential to redefine performance standards for high-end technical textiles, enabling new combinations of toughness, flexibility, permeability control and stability.

Biotechnology-enabled textiles also gain relevance in this phase. Bio-derived fibres, membranes and coatings, produced or pre-assembled in microgravity, will exhibit structural characteristics that are difficult to obtain on Earth, including improved purity, reduced defect formation and novel three-dimensional architectures. These developments will contribute to new families of sustainable materials that align with evolving European regulatory expectations on traceability, safety and circularity.

9.3 Consolidation of Space-to-Earth Industrial Transformation (2055–2060)

From the mid-2050s onward, the cumulative effect of decades of experimentation, in-orbit manufacturing and off-world construction will generate a structured return of technologies, processes and materials to terrestrial industries. This period marks the consolidation of a genuine space-to-Earth industrial cycle in which innovations originally developed for extreme extraterrestrial environments directly enhance the performance, sustainability and competitiveness of textile value chains on Earth.

Materials engineered for abrasion resistance, thermal stability, dust mitigation or low-maintenance operation will be re-designed for high-value applications in mobility, construction, personal protection, architecture and digital infrastructure. Sensorised textiles and adaptive membranes, initially developed for remote monitoring of pressurised environments, will support advanced industrial automation, predictive maintenance and occupant health monitoring.

Microgravity-manufactured fibres and composites will become the basis for new generations of lightweight structures, high-performance laminates, filtration systems and digital or hybrid textile products with enhanced homogeneity, reduced defect density and superior interfaces between fibres and matrices.

Bio-based materials synthesised or matured in microgravity will feed into sustainable textile production chains, supporting European objectives related to safety, reduced chemical impact and long-term circularity.

By the end of this horizon, technical textiles will evolve from specialised materials into fundamental enablers of next-generation industrial systems. Italy, due to its integrated value chain, leadership in surface engineering, and early role in cross-sector testbeds and demonstrators, will remain strongly positioned to shape and benefit from this transformation.

Projected long-term Cross-Sector Impacts

Across the 2031–2060 horizon, the cumulative effect of these developments will generate transformative impacts for both space and terrestrial industries. Technical textiles originally engineered for lunar, Martian or orbital applications will be re-designed for high-value sectors on Earth, enabling the widespread adoption of smart, durable and circular materials capable of delivering superior performance in mobility, personal protection, architecture and energy systems. Sensorised fabrics, self-healing membranes and adaptive textile-based components will increasingly support monitoring, automation and human safety across industrial environments.

At the same time, microgravity-manufactured fibres and composites, characterised by exceptional homogeneity, reduced defect formation and advanced interfacial properties, will give rise to new families of high-performance materials whose characteristics cannot be replicated under terrestrial gravity. Biotechnology-enabled fibres and membranes, formed in microgravity through highly ordered self-assembly processes, will further expand the range of sustainable and high-purity textile materials available to European industry. Together, these advances will contribute to reinforcing Europe's industrial competitiveness by integrating space-validated materials, processes and manufacturing paradigms into terrestrial value chains, transforming technical textiles from specialised components into foundational enablers of next-generation industrial systems.

10. Bibliography and External References

- CTNA Roadmap 2021-2023. https://agenda.infn.it/event/26924/contributions/136604/attachments/84715/112168/Leone%20CTNA%202021.pdf
- Interesting Engineering (2023). ESA tests antimicrobial materials for spacesuit inner linings. https://interestingengineering.com/innovation/esa-tests-antimicrobial-materials-for-spacesuit-inner-linings-that-do-not-require-washing
- ESA (2023). Keeping your underwear clean on the Moon. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Keeping_your_underwear_clean_on_the_Moon
- ESA (2024). ESA seeking dust-proof materials for lunar return. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_seeking_dust-proof_materials_for_lunar_return
- ESA Business Applications (2024). Webinar - Sustainable Textile.
- https://business.esa.int/sites/business/files/Webinar-Sustainable%20textile.pdf
- Editorial (2023). Next generation of materials for space applications. ResearchGate link.
- Holzer et al. (2023). Long-term preservation & monitoring of spacesuit displays. MDPI Sustainability. https://www.mdpi.com/2071-1050/15/12/9442
- Wiley/ResearchGate (2020). Advanced Materials for Future Lunar EVA Spacesuit.
- ESA Space Solutions (2024). Green Dossier. https://business.esa.int/sites/business/files/ESA%20Green%20Dossier%20MASTER_Digital_Final.pdf
- ESA Business Applications (2024). Greener Cotton. https://business.esa.int/projects/greener-cotton
- Beyond Gravity (2024). Thermal Insulation - MLI Multilayer Brochure. https://www.beyondgravity.com/sites/default/files/media_document/2024-04/Thermal%20Insulation%20Satellites%20Launchers%20MLI%20Multilayer%20Brochure.pdf
- ResearchGate (2021). Towards Safer Space Suits with Self-Healing Materials. AIAA (2023). Space Suit Boot Architecture. https://spacearchitect.org/pubs/AIAA-2023-4651.pdf
- ESA Nebula (2022). PExTex Executive Summary Report. https://nebula.esa.int/sites/default/files/neb_tec_studies/2906/public/ESR%20V1.0%20-%20PExTex%20-%20Executive%20Summary%20Report.pdf
- ESA Nebula (2023). PExTex Final Presentation. https://nebula.esa.int/sites/default/files/neb_tec_studies/2906/public/FP%20V1.1%20-%20PExTex%20-%20Final%20Presentation.pdf
- EURATEX (2024). Facts & Key Figures. https://euratex.eu/wp-content/uploads/EURATEX-Facts-Key-Figures-2024.pdf

- ASI TV (2024). Couture in Orbit. https://asitv.it/media/v/78be3ce4-5434-40b9-80b0-646206fc6afa/couture-in-orbit-from-spacewalk-to-catwalk
- ASI (2024-2026). PIAO. https://www.asi.it/wp-content/uploads/2024/10/Aggiornamento-PIAO-2024-2026.pdf
- ASI (2025). Italian Space Industry Catalogue. https://www.asi.it/wp-content/uploads/2025/01/Catalogo-ASI_160921_LOW.pdf
- ESA Nebula (2023). Aerobraking MLI Study. https://nebula.esa.int/4000133251

CTNA Cluster Tecnologico Nazionale Aerospazio

CONFINDUSTRIA MODA FEDERAZIONE TESSILE E MODA

esa TECHNOLOGY BROKER Italy

This white paper explores the strategic role of advanced technical textiles and engineered fabric solutions for future space applications.

It examines Italy's industrial capabilities and innovation pathways in developing high-performance textile-based technologies for the aerospace sector and outiines a roadmap for collaboration and technological advancement between the textile and space industries.