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Alternative Footwear Materials for the Outdoor Industry

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EDITORIAL INFORMATION

About this report

The European Outdoor Group has prepared this report in response to member requests for greater insight into alternative materials for footwear in the outdoor sector and the opportunities for material innovation, due to the need for a reduction in carbon emissions, and in alignment with emerging policy.

It is hoped that this report acts as a resource to stimulate further dialogue, collaboration, and innovation across the outdoor industry. By drawing attention to both challenges and opportunities, the report sets a foundation for continued engagement within the Footwear Working Group and beyond, ensuring that material innovation is not only aligned with regulatory requirements but also with the shared ambition of reducing environmental impact and supporting a more sustainable future for the sector.

While the primary focus of this report is on footwear, many of the alternative materials explored here have potential applications across other product categories within the outdoor sector. From apparel and accessories to equipment and packs, the innovations outlined may present opportunities to improve performance, durability, and sustainability in a wider range of products, reinforcing the value of shared learning and cross-category collaboration.



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ABOUT THE EUROPEAN OUTDOOR GROUP (EOG)

“We are the voice of the European outdoor sector. Our vision is to do global, profitable business in a way that gives back more than we take from nature and from people”.

We undertake a wide range of activities, including market insights, corporate social responsibility and sustainability initiatives, outdoor retail collaboration, organising and supporting industry events and trade fairs, and representing our sector and its interests to the European Commission, NGOs, formal institutions, and other stakeholders.

Recognising the need for a cohesive, cross border approach to representation of the outdoor sector, the European Outdoor Group was founded in 2005 by 19 of the world’s largest outdoor companies. The association has grown steadily to include retailers, national associations, and technology providers. Now totalling 150 members, the combined strength of our members delivers an extremely powerful force to represent the European outdoor industry in a constructive and positive manner.



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1. INTRODUCTION

Globally, the footwear sector produces over 23 billion pairs annually, with Asia dominating both production and consumption (World Footwear Yearbook, 2025). Within Europe and based on the figures obtained by State of Trade it is believed that footwear within the outdoor sector accounted for approximately 22.4% of the market share on average between 2022 and 2024 and was estimated to have the second highest value compared to apparel, valued at €375 million in 2024 (EOG, 2025).

However, this immense scale brings significant environmental consequences throughout the life cycle of footwear products, including material extraction, manufacturing, use, and disposal phases (Muthu, 2013). Conventional materials such as leather, synthetics, and rubber not only require resource intensive production but some of these materials pose challenges at end-of-life due to their poor biodegradability and complex recycling processes (Rahimifard, 2014). According to the Life Kanna Green Project funded by the European Commission, the waste generated from used footwear is thought to be approximately 1.2 million tons per annum, of which it is estimated that only 5% is recycled, 15% is reused and 80% is landfilled (European Commission, 2024).

Outdoor Footwear in Europe - Percentage Market Share (Volume) 2022-2024

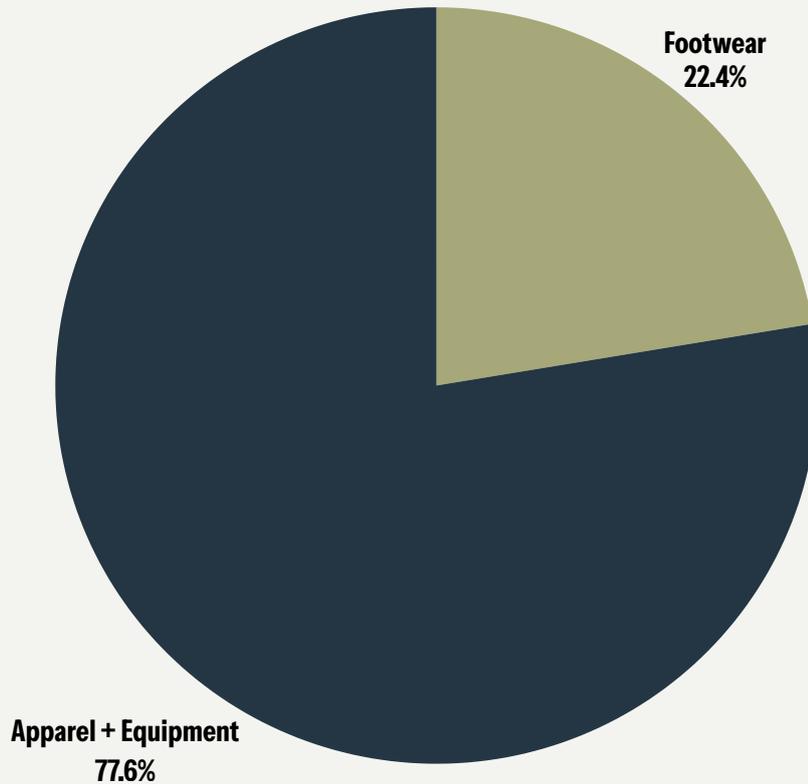


Figure 1: Percentage market share (volume) of footwear in the Outdoor Industry (based on data from State of Trade Report by EOG)

As brands strive to reduce their environmental footprint, there is growing recognition that material innovation plays a critical role in achieving sustainability targets. Life-cycle assessment studies have highlighted that material choices often account for the majority of footwear's environmental impacts (Muthu, 2013).

The aim of this report is to look at current footwear materials used in the outdoor industry, touch on their environmental implications, and explore promising alternative solutions that align with circular economy principles and emerging regulatory pressures.



2. CURRENT FOOTWEAR MATERIALS

Outdoor footwear, including walking boots and climbing shoes, are engineered to meet rigorous performance demands under extreme environmental conditions. The materials used directly influence comfort, durability, waterproofing, weight, and grip critical factors for outdoor enthusiasts.

According to the Materials Market Report 2024, leather and synthetic materials dominate the global footwear material share. Leather accounts for approximately 60–65% of the material in footwear, especially in premium hiking boots. However, synthetic options such as PU, nylon, and rubber dominate climbing shoes due to their customisable performance and recyclability potential (Textile Exchange, 2024).

Detailed below is a breakdown of the of the common materials used in a walking boot and climbing shoes as examples, followed by the advantages and disadvantages of these materials.

2.1 Walking Boot Materials

Upper Materials (Vamp, Tongue, Collar, Toe Cap & Heal Counter)

Walking boots typically use a combination of natural and synthetic materials:

- Full-grain and nubuck leather: These provide excellent abrasion resistance, durability, and water repellency, though they require a break-in period and regular care (Lockwoods, 2025; Camotrek, 2023).
- Synthetic fabrics (e.g. nylon, polyester): Often used to reduce weight and improve breathability. Thermoplastic polyurethane (TPU) overlays add structure and protection without the bulk of leather (Lowa, 2025).
- PVC-coated plastics are used in some mountaineering models but are not ideal for breathability or long-distance hiking (Camotrek, 2023).

Lining and Waterproofing

- GORE-TEX®, eVent®, sympatex® and other breathable membranes are bonded to linings to prevent water ingress while allowing perspiration to escape (Lowa, 2025).
- Leather linings may offer better in-shoe climate control but are heavier and require more care (Lowa, 2025).

Midsoles

- EVA (Ethylene-Vinyl Acetate) midsoles are common for lightweight cushioning, while polyurethane (PU) is preferred in boots for long-distance or rugged terrain due to its superior support and durability (Camotrek, 2023; Advnture, 2025).
- Insoles are often foam-based and removable, offering customization and orthotic compatibility (Camotrek, 2023).

Outsoles

- Rubber outsoles (e.g. Vibram®) dominate the market for their traction and abrasion resistance. Deep lugs are used for muddy terrain, while flatter patterns suit rock and dry trails (Lockwoods, 2025).

Adhesives & Glues

- Common glue types include urethane, neoprene-based contact cement, hot-melt glues, and natural rubber-based adhesives, chosen based on flexibility, waterproofing, and bond strength (Camotrek, 2023). The upper may use water-based adhesives and for the sole attachment, a polyurethane-based adhesives is more common.
- These adhesives not only play a structural role but also influence whether the boot can be resoled or repaired later.



Graphic of a walking boot - AKU

2.2 Climbing Shoe Materials

Climbing shoes demand precision, sensitivity, and grip. Their construction is tailored to varying climbing styles, such as sport, trad, bouldering and user experience levels.

Upper Materials

- Leather uppers stretch with wear, conforming to the climber's foot. However, they are more prone to odour and sweat absorption (Alpinetrek, 2025).
- Synthetic materials (e.g., microfiber, synthetic suede) offer reduced stretch and better odour control (Climbing Shoe Review, 2023; Scarpa, 2024).

Lining

- Some climbing shoes are unlined which provide better sensitivity but less comfort.
- Lined shoes use cotton or synthetic linings to reduce stretch and maintain shape (Scarpa, 2024).

Midsole and Tensioning Systems

- Midsole stiffness varies by use: softer for smearing and toe flexion, stiffer for edging.
- Tensioning systems such as the P3® platform or slingshot rand hold the shoe's aggressive shape, improving power transmission (Rock Spot Climbing, 2025).

Outsole Rubber

- High-friction rubber compounds like Vibram® XS Grip2 and Stealth® C4 are used to maximise grip, sensitivity, and durability on rock (Scarpa, 2024).
- Rubber thickness varies across models: thinner soles improve feel; thicker soles last longer (Climbing Shoe Review, 2023).

Adhesives

- Typically heat-activated contact cements secure the rand (upper rubber) and sole during lasting and final assembly (Camotrek, 2023).



Graphic of a climbing shoe - Decathlon

Table 1: Summary of Materials Used in Outdoor Footwear

Component	Common Materials	Adhesives / Glue Role
Upper	Suede, Full Grain Leather, Nubuck Leather, Polyester, Polyamide, e-PE, e-PTFE	Hot-melt, neoprene, urethane cements for lamination/water based.
Midsole	EVA (compression moulded, supercritical, injected, microporous), PU (injected, poured), Rubber	Bonded to upper/outsole via adhesives
Outsole	Rubbers	Cemented; needs strong, flexible bonds
Climbing Shoe	Leather/synthetic, eg. PET/nylon, rubber soles/ cotton linings	Specialized adhesives for lasting performance



2.4 Leather

Leather has been a cornerstone of the textile and fashion industries for centuries, prized for its durability, versatility, and luxury appeal (Wang, 2024). Despite its prominence, the production, processing, and consumption of leather have sparked debates regarding sustainability, ethics, and environmental impact (Chen et al., 2023; D'Adamo et al., 2024). This analysis explores the positive and negative attributes of leather and the implications for sustainable textile production.

03.4.1 Positive Attributes of Leather

Durability and longevity

One of the strongest advantages of leather is its exceptional durability. Traditional animal-based leather often outlasts synthetic and plant-based alternatives, providing better long term value to consumers (D'Adamo et al., 2024). Its resistance to wear, combined with proper care, makes it a preferred choice for high quality apparel, accessories, and upholstery.

Consumers often cite durability, aesthetics, and quality as the most important characteristics of leather, consistently rating them between 4 and 5 on a 5-point scale across demographics (D'Adamo et al., 2024, p.19).

Aesthetic and sensory appeal

Leather maintains a premium tactile and visual appeal, with a natural texture and finish that synthetic or vegan alternatives struggle to replicate (Wang, 2024). Its ability to age gracefully, developing a unique patina over time, enhances its aesthetic and resale value.

Biodegradability and circular potential

Unlike many petroleum-based synthetics, animal leather is naturally biodegradable under proper conditions (Wang, 2024). Some industry associations argue that leather production supports a circular economy, as hides are by-products of the meat industry that would otherwise contribute to landfill waste (Chen et al., 2023).

Functional versatility

Leather's breathability, comfort, and adaptability across applications from high-fashion apparel to sports equipment and automotive interiors, reinforce its position as a versatile textile material (Nayak et al., 2023).

03.4.2 Negative Attributes of Leather

Environmental impact

Leather production is resource-intensive. Studies highlight high water consumption, greenhouse gas emissions, and chemical pollution, especially during the tanning process (Hildebrandt et al., 2021; Chen et al., 2023).

- Water usage: Up to 300 m³ of water can be consumed during tanning and finishing per tonne of hides processed (Retracted LCA Report, 2023, p.4).
- Chemical contamination: Chromium-based tanning processes release hazardous chemicals into ecosystems, endangering both environmental and worker health (D'Adamo et al., 2024, p.9).
- Carbon footprint: Cattle rearing for leather contributes significantly to CO₂ emissions and deforestation (Mammadova et al., 2020).

Ethical concerns

Leather production raises animal welfare issues, with increasing consumer demand for cruelty-free products driving interest in vegan and synthetic alternatives (D'Adamo et al., 2024; Wang, 2024).

Social and occupational risks

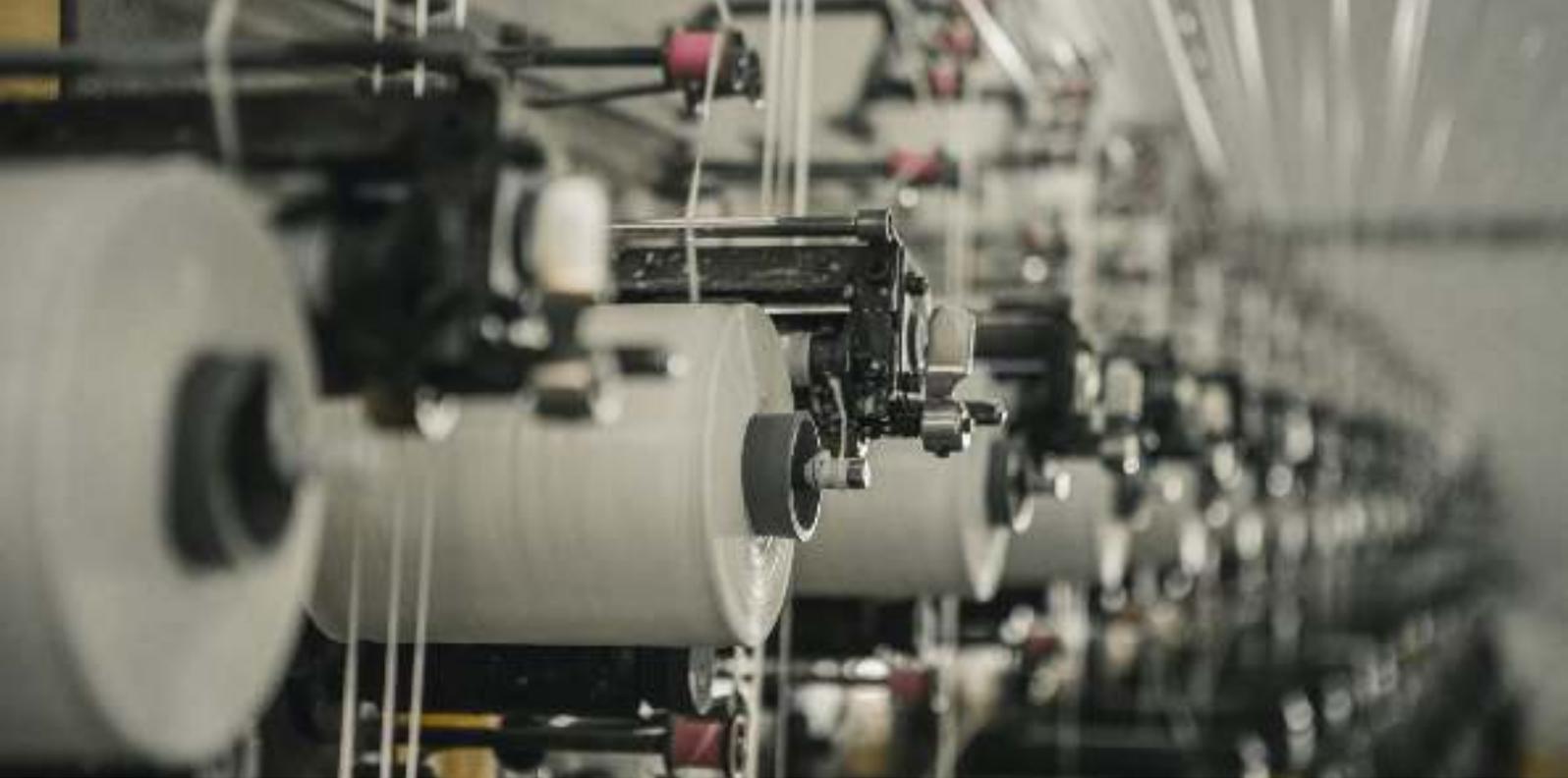
In developing countries, inadequate safety measures in tanneries expose workers to toxic chemicals and unsafe conditions (Chen et al., 2023). Lack of stringent environmental regulations in these regions exacerbates both social and ecological damage.

Limited recycling and waste issues

While the circular potential of leather is touted, post-consumer recycling remains limited, with most leather waste sent to landfill or incinerated (Aymard et al, 2019).

Sustainable supply chain management practices are critical to reducing the negative impacts of traditional leather production (Chen et al., 2023). Key approaches include:

- Cleaner tanning technologies such as chromium recycling and enzymatic tanning (D'Adamo et al., 2024, p.10).
- Supply chain transparency and certification systems to improve traceability and consumer trust (Aymard et al, 2019).
- Investment in circular business models that enable material reuse and upcycling (Chen et al., 2023).



2.5 Synthetic Materials

Synthetic materials are used frequently in modern footwear manufacturing due to their versatility, durability, and cost-effectiveness. Materials such as polyester, nylon, polyurethane (PU), ethylene-vinyl acetate (EVA), and rubber offer a wide range of functional properties that natural materials often cannot match, including enhanced strength, abrasion resistance, water resistance, and lightweight performance (Ahmad et al., 2023; Sun et al., 2020). The rise of synthetic polymers in footwear dates back to the mid-20th century, driven by advances in polymer chemistry and growing consumer demand for affordable, high-performance shoes suitable for sports, work, and everyday wear (Liu et al., 2023). Today, synthetics enable manufacturers to engineer specialized footwear with tailored properties such as improved cushioning, flexibility, and energy return, while supporting mass production and innovative design processes, including 3D knitting and additive manufacturing (Kumari and Manshahia, 2025; Ghimouz et al., 2023). This combination of performance, adaptability, and economic efficiency explains why synthetic materials dominate the global footwear market.

Below this report explores the positive and negative attributes of synthetic materials and addresses their implications.

2.5.1 Positive attributes of Synthetic Materials

Good performance characteristics

Polyester, nylon, polyurethane (PU), ethylene-vinyl acetate (EVA), and rubber have transformed modern footwear design and performance. These materials are lightweight, durable, and versatile, making them suitable for a range of applications from athletic shoes to casual and safety footwear (Ahmad et al., 2023; Sun et al., 2020). Polyester and nylon, for example, offer high abrasion resistance, dimensional stability, and moisture-wicking properties, which make them ideal for shoe uppers and linings (Ahmad et al., 2023).

Polyurethane and EVA have been particularly impactful in midsole and insole design. PU offers tunable hardness, flexibility, and chemical resistance, enabling manufacturers to engineer shoes with specific performance profiles such as enhanced cushioning, stability, and energy return (Liu et al., 2023; Brückner et al., 2010). EVA foams, meanwhile, are valued for their shock absorption and flexibility, providing comfort and reducing fatigue during prolonged wear (Sun et al., 2020). Rubber, commonly used in outsoles, delivers excellent traction, abrasion resistance, and resilience under different temperature conditions, making it essential for sports and outdoor footwear (Ahmad et al., 2023).

Technological innovations such as 3D knitting, weaving, additive manufacturing (AM), and nanotechnology have further enhanced the performance and customisation of synthetic footwear materials (Kumari and Manshahia, 2025). Ergonomic designs now integrate foot biomechanics, arch types, and gait patterns, reducing injury risks and improving user comfort and athletic performance (Kumari and Manshahia, 2025). Additive manufacturing techniques, including selective laser sintering (SLS) and multi-jet fusion (MJF), also enable modular, lightweight components that enhance recyclability and reduce material waste (Ghimouz et al., 2023).

2.5.2 Negative attributes of Synthetic Materials

Despite their functional advantages, synthetic materials pose significant environmental and sustainability challenges.

High emission rates

Polyester, nylon, and PU are petroleum-based polymers that require high energy inputs during production and emit substantial greenhouse gases (Ghimouz et al., 2023; Baloyi et al., 2023).

Microplastic shedding

Microplastic shedding from polyester and nylon during use contributes to environmental pollution, impacting ecosystems and entering food chains (Baloyi et al., 2023). This is also growing evidence to suggest that rubber 'grind' from the soles of shoes is contributing to this environmental pollution.

Low recyclability

Recycling synthetic footwear materials remains limited and inefficient. Globally, only about 5% of footwear is recycled, while the majority of shoes are incinerated or sent to landfills at the end of their life cycle (Ghimouz et al., 2023). Complex polymer structures, such as those in PU and EVA, hinder recycling and circularity due to their chemical crosslinking (Liu et al., 2023). Although chemical recycling methods, such as depolymerization of nylon-6 into caprolactam, show promise, they are energy-intensive and not yet widely scalable (McNeeley and Liu, 2024).

Low biodegradability

Another issue is the low biodegradability of these materials. Synthetic shoes can take hundreds of years to decompose, contributing to the growing problem of textile and footwear waste (Baloyi et al., 2023).

Release of hazardous chemicals

Production processes for PU and other synthetics may release hazardous chemicals and volatile organic compounds (VOCs), posing occupational health risks and environmental hazards (Liu et al., 2023).



3.0 RECYCLED MATERIALS AND PROCESSES

3.1 Mechanical Recycling

Mechanical recycling is the most established method of textile-to-textile recovery and involves the physical breakdown of fabrics into fibers without altering their chemical structure. It is particularly effective for textiles with high mechanical strength and simple compositions, but it becomes significantly more challenging when dealing with blended fabrics, multi-material garments, or those with extensive chemical finishes (Seifali Abbas-Abadi et al., 2025). Pre-consumer waste tends to be more suitable for mechanical recycling due to lower levels of contamination, whereas post-consumer waste requires more complex sorting and removal of accessories, dyes, and finishing agents before processing (Abrishami et al., 2024). Despite its operational maturity, mechanical recycling leads to the progressive shortening and weakening of fibers, meaning the resulting material is often of lower quality and cannot be recycled indefinitely.

3.2 Thermal Recycling

Thermal recycling processes recover value from textile waste by using heat to break polymers into smaller molecules or secondary raw materials. Methods such as pyrolysis, melt re-extrusion, and gasification are especially relevant for synthetic textiles like polyester, which can be thermally decomposed into oils, gases, or syngas (Seifali Abbas-Abadi et al., 2025).

These processes are particularly useful when contamination or material complexity makes mechanical or chemical recycling unfeasible. However, thermal recycling is energy-intensive and typically results in downcycling rather than the production of new, high-quality textile fibers.

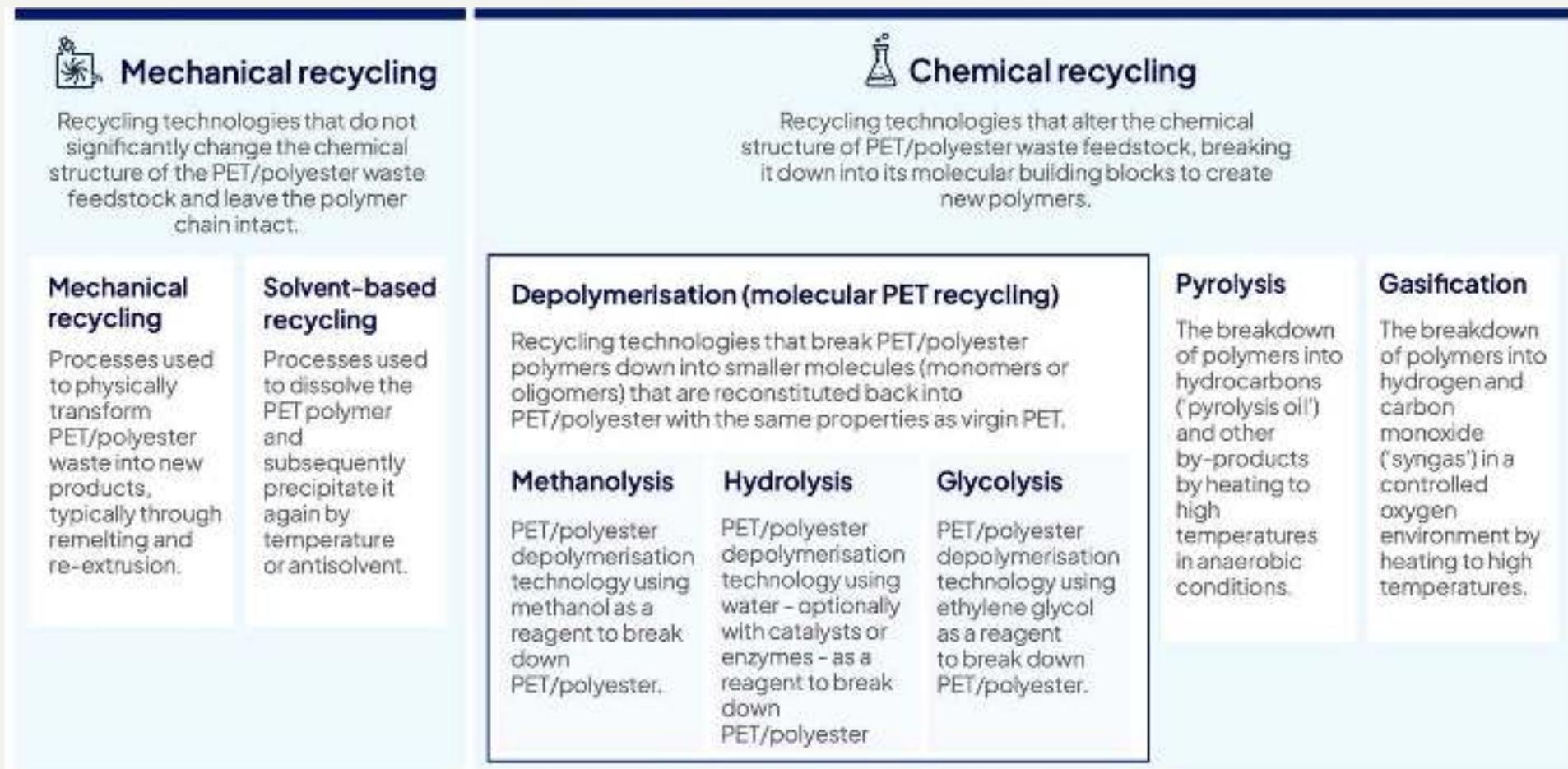
3.3 Chemical Recycling

Chemical recycling is widely viewed as a critical pathway to achieving circularity in the textile sector because it breaks polymers down into their original monomers, allowing them to be repolymerised into virgin-quality fibers. Processes such as solvolysis, hydrolysis, and alcoholysis can selectively target polymers like polyester, nylon, and cellulose (Seifali Abbas-Abadi et al., 2025). Chemical depolymerisation technologies for polyester—especially PET—have advanced significantly and can provide virgin-equivalent outputs suitable for high-performance textile applications (Systemiq, 2025). However, cost barriers remain a significant challenge, with chemically recycled polyester currently more expensive than virgin material and reliant on access to clean, well-sorted feedstocks. Overcoming these limitations will require coordinated policy action, improved waste-sorting infrastructure, and greater industry collaboration (Systemiq, 2025; Abrishami et al., 2024).

Summary

Taken together, mechanical, thermal, and chemical recycling methods each contribute to a potential circular textile system. Mechanical recycling is mature but limited by fiber degradation; thermal methods extend recovery to contaminated or complex waste streams but produce lower-value outputs; and chemical recycling offers true fiber-to-fiber potential, especially for polyester, though it requires further scaling and policy support. Addressing persistent challenges around waste collection, sorting, contamination, and the high prevalence of blended garments is essential to unlock the full environmental benefits of these recycling pathways (Abrishami et al., 2024).

Figure 2 - Mechanical and Chemical Recycling Processes
 Diagram taken from the SYSTEMIQ report May 2025 (Systemiq, 2025)





3.4 Recycled Synthetic Materials

3.4.1 Recycled Polyester

Recycled polyester (rPET) is a major focus of sustainable footwear design due to its versatility, durability, and role in reducing reliance on virgin petrochemicals. It is widely used for uppers, linings, laces, and knitted components. Innovations in rPET filament production now enable 100% recycled fibres with mechanical properties comparable to virgin polyester, improving shape retention and tensile strength (Ecotextile, 2024a). Companies such as Reju have advanced chemical recycling of polyester waste into regenerated feedstock, producing materials that reportedly lower carbon emissions by 50% compared to virgin PET (Reju, 2025). These industrial-scale regeneration hubs provide brands with scalable recycled inputs. Samsara Eco complements this by using enzymatic recycling to process PET blends and coloured fabrics (Samsara Eco, 2025).

To accelerate the adoption of recycled PET into products within the outdoor sector, the European Outdoor Group (EOG) is working with Reju, and the non-profit Accelerating Circularity to integrate recycled polyester into outdoor footwear and apparel supply chains. Such collaborations are hoped to enable EOG members to overcome barriers in sourcing, traceability, and recycled content verification.

3.4.2 Recycled Nylon

Nylon remains a critical fibre for performance footwear, especially in technical uppers and linings, due to its abrasion resistance and elasticity. Recycling nylon, however, is more energy intensive than polyester. Innovations are emerging to address this: BASF launched production of recycled nylon 6 in China in 2025 to establish a scalable circular system for polyamide fibres (Ecotextile, 2025b). Samsara Eco's enzymatic technology enables depolymerisation of nylon 6 and nylon 6,6, even in blended or dyed textiles, offering potential for "infinite recycling without quality loss" (Ecotextile, 2024b; Samsara Eco, 2025).

The European Outdoor Group has identified nylon as a priority fibre, and it now working with Samsara Eco to connect members to recycled nylon supply chains in a group called the Nylon Materials Collective. By combining chemical and enzymatic routes, nylon recycling may soon provide consistent, high-quality materials for sports and outdoor footwear, although cost and scalability may remain as barriers (Abrishami et al., 2024).

3.4.3 Recycled EVA

Ethylene-vinyl acetate (EVA) is widely used for midsoles and outsoles, prized for its light weight and cushioning properties. Recycling EVA is technically challenging because of crosslinking during foaming, but several studies demonstrate its feasibility. Junior et al. (2022) showed that pre-vulcanised EVA waste can be shredded and incorporated into virgin EVA, while Bianchi et al. (2023) found that adding 10% recycled EVA maintains acceptable mechanical properties and delivers substantial environmental benefits through Life Cycle Assessment (LCA). Although recycled EVA shows slightly lower tensile and abrasion resistance than virgin grades, the sustainability and cost benefits are considerable.

Optimisation studies in sports footwear also confirm the value of EVA recovery in reducing waste and enabling zero-waste production loops (Loganathan et al., 2024). Industrialisation, however, is still in early stages, with recycling processes mostly limited to fillers and blends rather than high-performance midsoles.

3.5.4 Recycled Rubber

Rubber, especially in outsoles, is traditionally difficult to recycle due to vulcanisation. New European initiatives, however, are exploring grinding, micronisation, and devulcanisation to recover rubber from post-consumer soles (Re_fashion, 2025). These methods can reintroduce rubber into new soles or open-loop products such as flooring. Nike's long-standing Grind programme illustrates the feasibility of recovering rubber from both pre- and post-consumer shoes, and Re_fashion highlights the need for automated dismantling to separate rubber from multi-material soles (Re_fashion, 2025).

Circular economy models suggest that incorporating recycled rubber could cut carbon emissions by over 80% compared to conventional shoes (Pantazi-Băjenaru et al., 2023). However, costs, sorting difficulties, and material contamination remain barriers to large-scale uptake.

Summary

Together, recycled polyester, nylon, EVA, and rubber represent key levers for reducing the environmental footprint of footwear. Polyester and nylon benefit from rapid advances in chemical and enzymatic recycling, driven by innovators like Reju and Samsara Eco, while coalitions such as Accelerating Circularity and the European Outdoor Group are helping brands embed these materials into their supply chains. EVA and rubber recycling, though technically more complex, show strong potential when combined with LCA-driven optimisation and industrial trials. Moving forward, scaling these systems, alongside transparent labelling, durable product design, and improved dismantling infrastructure, will be essential to transition footwear towards a circular economy.



4. THE NEED FOR ALTERNATIVE MATERIALS

The outdoor footwear industry faces mounting sustainability challenges due to its material intensive, high-impact production processes. Traditional materials such as leather, synthetic polymers (e.g. PU, EVA, PVC), and rubber not only involve significant resource consumption but also hinder end-of-life recycling due to the complexity of multi-material shoe constructions (Muthu, 2013; Jadhav & Jadhav, 2020). A typical shoe can contain over 40 different components and material types, making disassembly and recycling extremely difficult (Rahimifard, 2014; Muthu, 2013).

Globally, footwear production exceeds 20 billion pairs annually, with the majority ending up in landfills or incinerated. The EU alone produces an estimated 1.2 million tonnes of footwear waste per year, with less than 5% being reused or recycled (Rahimifard, 2007; Rahimifard, 2014). This trend is exacerbated by fast fashion, rising consumption rates, and limited recycling infrastructure. Traditional recycling approaches are economically unviable due to the low residual value of many footwear materials and the lack of automated, scalable recycling technologies for complex material blends (Rahimifard, 2014).

A life cycle perspective reveals that materials are the most carbon-intensive stage of footwear production. For instance, AKU, an Italian outdoor footwear manufacturer, calculates the CO₂ footprint of its products using ISO-compliant methods (ISO 14067, 14040, and 14044) verified by Bureau Veritas.

Their IMPACTO model shows that materials contribute over 60% of emissions in products like mountaineering boots (AKU, 2024). The Hayatsuki GTX model, for example, has a footprint of 35 kg CO₂e per pair, while lighter synthetic models can be under 10 kg CO₂e. Comparisons between leather and synthetic/recycled variants of the same shoe show a 30–60% emissions reduction when using alternative materials (AKU, 2023).

Despite this, AKU emphasizes a balanced material strategy, acknowledging that leather, when responsibly sourced as a meat industry by-product can offer durability and long service life, potentially lowering impacts over time. This reflects a broader industry need to adopt evidence-based material selection, rather than blanket elimination of specific materials.

To meet these challenges, the industry is increasingly turning to next-generation (next-gen) materials. These include textile-to-textile recycled synthetics, lab-grown leather alternatives, mycelium-based foams, and plant-based polymers, offering significant reductions in environmental impact and circularity potential (Fashion for Good & BCG, 2025; MII, 2021). However, more than 80% of fashion and footwear brands currently lack sustainable sourcing targets across key material categories such as leather, cotton, polyester, and nylon (Fashion for Good & BCG, 2025).

Moreover, climate change is intensifying resource volatility. For instance, extreme weather in Pakistan and Australia has significantly reduced cotton and wool yields, further supporting the case for material diversification (Fashion for Good & BCG, 2025). As the regulatory landscape tightens in Europe and consumer demand for ethical materials rises, embracing next-gen innovations has become a business imperative (MII, 2021).

Life cycle assessment (LCA) studies confirm that slaughtering, tanning, and cotton production are some of the most environmentally damaging phases in leather shoe supply chains (Rossi et al., 2021). Substituting these inputs or adopting low-impact versions, such as regenerative cotton or mycelium leather, could reduce emissions by over 30%, especially when combined with logistics and process optimizations.

Despite these advances, the industry still lacks scalable infrastructure for recycling, particularly for worn or damaged shoes. While programmes like Nike's Reuse-A-Shoe initiative recover some materials from athletic shoes, most footwear types remain excluded due to complex construction and low economic value of recovered materials (Rahimifard, 2014).

4.1 The Impact of European Policy

EU policies are rapidly transforming how footwear is designed, manufactured, and disposed of. The introduction of Product Environmental Footprint Category Rules (PEFCR) for apparel and footwear has established a standardized, science-based methodology for assessing life-cycle environmental impacts, from raw materials to end-of-life (European Commission, 2025). These rules require manufacturers to quantify the environmental footprint of each material used, creating pressure to reduce impacts across the value chain. As a result, footwear producers must now account for all components, including adhesives, leathers, and synthetic foams, under transparent, verifiable criteria (PEF Apparel & Footwear, 2025).

Simultaneously, the Ecodesign for Sustainable Products Regulation (ESPR) expands the EU's power to set product-specific sustainability requirements (European Commission, 2024a). The regulation mandates design for durability, repairability, recyclability, and material transparency. A significant clause bans the destruction of unsold textiles and footwear (European Commission, 2024a), encouraging producers to focus on circular business models, such as repair, refurbishment, and resale (Repair.EU, 2024). This regulatory framework compels footwear manufacturers to rethink their product life cycles, incorporating new materials that can be easily disassembled or recycled, for example, modular soles, recyclable thermoplastic elastomers, and bio-based polymers.

The Waste Framework Directive (WFD) complements these policies by promoting separate collection, reuse, and recycling of textiles and footwear waste (European Commission, 2023). It lays the foundation for Extended Producer Responsibility (EPR) schemes, which make producers financially accountable for the entire life cycle of their products, including take-back and recycling (European Commission, 2023). Under EPR, companies face higher fees for products that are difficult to recycle or repair, while circular and recyclable designs may benefit from reduced fees (Carbonfact, 2024). This economic incentive encourages firms to innovate with materials and processes that lower waste generation and environmental burden.

Collectively, these measures are accelerating the adoption of new materials in footwear production. Manufacturers are investing in low-impact and recyclable materials, as well as digital product passports (DPPs) that track the origin, composition, and recyclability of shoes (CEC Footwear Industry, 2024). Such transparency not only facilitates compliance with EU regulations but also enhances consumer trust and brand competitiveness in a market increasingly defined by sustainability standards. Ultimately, the convergence of PEFCR, ESPR, WFD, and EPR policies is driving a systemic shift from a linear to a circular footwear economy.



5. ALTERNATIVE MATERIALS - BIO-BASED

Bio-based materials can be broadly defined as a material derived from biological sources or designed to interact with biological systems, either for medical purposes or sustainable product development.

Originally, the term was closely associated with medical science, where biomaterials were engineered to replace or support human tissues and organs (Ferreira et al., 2023). However, over time the concept has expanded, and in textiles and product design, and biomaterials now include fibres and composites made from renewable, bio-based, or biodegradable resources, such as natural fibres, biopolymers, and next-generation synthetics (Deckers et al., 2023; Liu et al., 2024).

Biomaterials differ significantly from conventional petroleum based synthetics like polyester or nylon. Whereas the latter rely on finite fossil resources, biomaterials often originate from plants, animals, microorganisms, or even agricultural and industrial by-products. For example, cotton, hemp, silk, and wool are traditional biomaterials, while bio-regenerated fibres like viscose or advanced synthetic biopolymers such as polylactic acid (PLA) represent newer developments (Liu et al., 2024; Tian et al., 2022). These materials are valued not only for being renewable but also, in many cases, for their potential biodegradability and lower carbon footprint compared to fossil-based alternatives (Tian et al., 2022). However, it is important to note that being bio-based does not necessarily mean a material is biodegradable; some require specific industrial conditions to decompose effectively (Ferreira et al., 2023).

Although bio-based and non-isocyanate polyurethane (NIPU) alternatives are being researched to reduce dependency on petroleum sources, these solutions often come with trade-offs, such as lower mechanical performance or challenges with industrial scalability (Liu et al., 2023). Similarly, while recycled polyester (rPET) is increasingly used, much of it still originates from PET bottles rather than true post-consumer textile recycling, limiting progress toward a fully circular model (Baloyi et al., 2023).

In the context of sustainability, biomaterials play a vital role in reducing the environmental impacts of industries like fashion, footwear, and automotive. They offer opportunities to mitigate greenhouse gas emissions, limit microplastic pollution, and enable circular practices such as recycling and composting (Bulman, 2022; Roberts-Islam, 2022). Innovations in biomaterial science include composites made from recycled polymers and natural fillers (Alexandrescu et al., 2020), bioengineered textiles from mycelium or microbial fermentation (Material Innovation Initiative, 2021), and bio-based synthetics that can rival petroleum-derived fibres in durability and performance (Roberts-Islam, 2022).

Overall, biomaterials represent a convergence of biology, materials science, and sustainability. Their diversity from traditional natural fibres to lab grown leather alternatives illustrates both their flexibility and their growing importance in the global shift toward a circular economy. They are not a single category of materials but rather a broad and evolving field defined by renewable origins, ecological responsibility, and adaptability across multiple industries.

Figure 3 - Bio-based vs Biodegradability

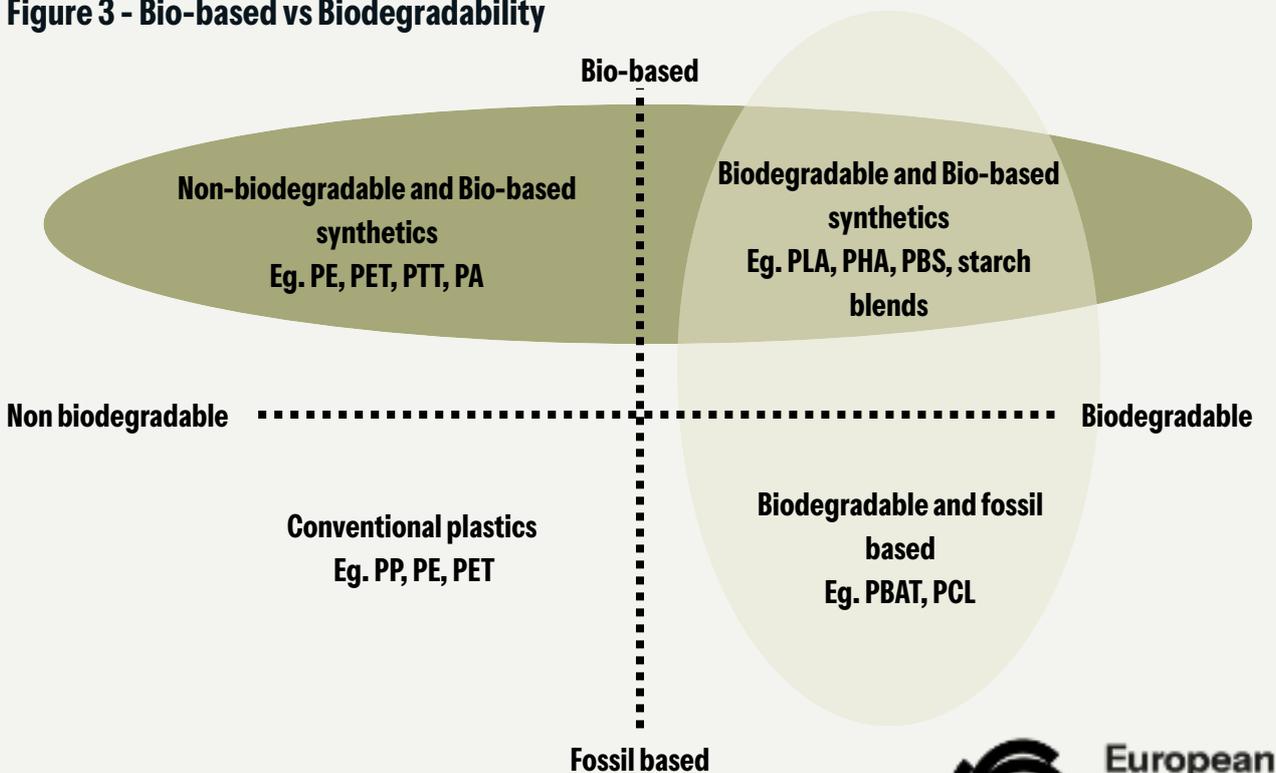
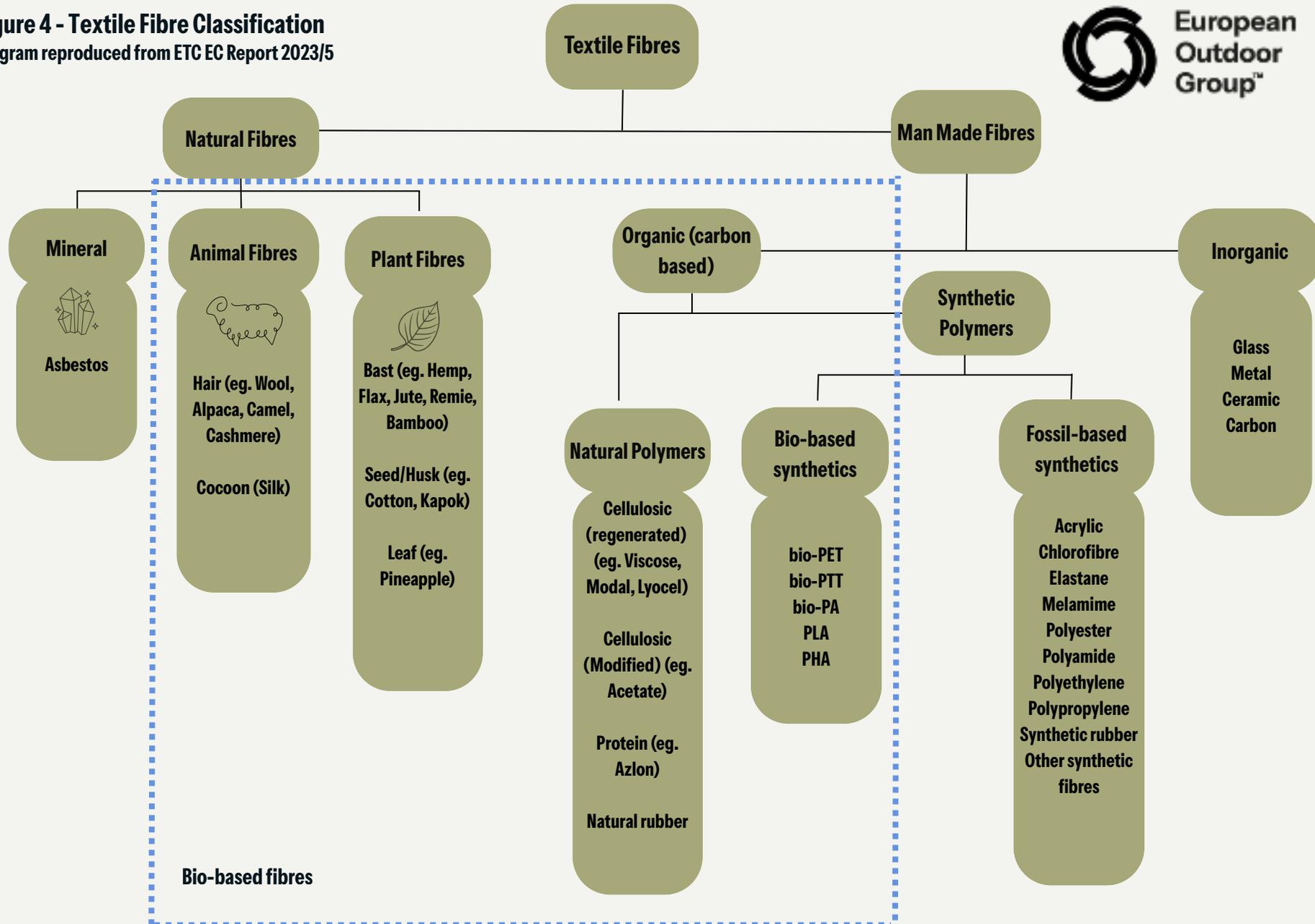


Figure 4 - Textile Fibre Classification
 Diagram reproduced from ETC EC Report 2023/5





5.1 Algae based materials

Algae based materials are gaining attention in textiles and footwear because they offer renewable, biodegradable, and versatile alternatives to conventional fibres and plastics. The textile industry has long faced criticism for its heavy reliance on petrochemicals, water, and toxic dyes, making algae an appealing resource due to its abundance, fast growth, and minimal land requirements (Ayyanar et al., 2023).

Algae-derived fibers, films, and composites can be engineered into fabrics that are breathable, lightweight, and even functional, with potential antimicrobial or UV-protective properties. This makes them promising candidates for sustainable textile materials, as they reduce dependence on fossil-based fibres while aligning with circular economy goals (Rognoli et al., 2022).

In textiles, algae based biopolymers are being processed into threads and films that mimic synthetic fibres but biodegrade at end-of-life, offering an important response to microplastic pollution (Ayyanar et al., 2023). Researchers and designers are already experimenting with algae blends to create textiles with unique tactile and aesthetic qualities, linking material development directly to consumer experiences of sustainability (Rognoli et al., 2022).

Footwear applications follow a similar track but focus heavily on material durability, flexibility, and end-of-life management. By introducing algae-based foams, films, and composites, designers aim to replace petroleum-derived EVA foams or polyurethane components, which are among the footwear industry's most problematic pollutants.

Biodegradable algae foams have already been tested in midsoles and insoles, where comfort and cushioning are key. Combined with other bio-based textiles or leathers, algae-derived materials help reduce the massive landfill impact of discarded shoes (Zavodna, Trejtnarová and Pospíšil, 2020).

MATTR™ by REVOLTRCH

A promising algae based leather alternative material is MATTR™, developed by the German materials innovator Revoltech GmbH. Entirely plant-based and free from synthetic plastics like PU or PVC, it embraces a biodegradable composition that supports circular economy principles. Derived from rapidly renewable algae which can even thrive in wastewater and requires minimal resources, MATTR™ combines environmental responsibility with tactile versatility. Despite its delicate feel, the material exhibits impressive durability, flexibility, and abrasion resistance, making it suitable for many applications across the apparel, footwear and interior sectors. Offered in a customisable range of colours and finishes, MATTR™ balances aesthetic appeal with sustainability, serving as an innovative, animal free alternative to conventional leather -

<https://www.revoltech.com/mattr>

VEERAH

Veerah's innovative algae foam cushioning, harnesses the potential of excess algae often seen as harmful to provide eco-friendly comfort.

By processing algae filled water, the company not only purifies and returns water to the environment, but transforms the harvested algae into a fine powder that replaces over 30% of petroleum content in traditional foam. The result is a soft, lightweight, and durable insole that reduces ecological impact: each pair is said to conserve 11 gallons of filtered water and prevents the release of eight balloons worth of CO₂ into the atmosphere.

<https://www.veerah.com/>



5.2 Bio-Foam Materials

Bio-based foams are emerging as an important alternative to petroleum-derived polyurethane (PU) foams in the footwear sector. Conventional PU foams, widely used for midsoles and insoles, are typically produced from fossil based polyols and isocyanates, raising concerns about carbon emissions and end-of-life disposal (Santos et al., 2025). In contrast, bio-based PU foams replace fossil-derived polyols with renewable feedstocks such as vegetable oils, lignocellulosic biomass, and carbohydrates, which can significantly reduce the environmental footprint of footwear manufacturing (Desai et al., 2023).

Companies such as Insite are working towards developing foams with 100% bio-based polyol content, demonstrating the feasibility of scaling these materials in commercial footwear applications (Insite, 2025).

From a performance perspective, bio-based foams show promising properties for use in footwear cushioning. Studies have highlighted that bio-derived polyols can yield foams with comparable resilience, elasticity, and energy absorption to conventional PU foams, while also introducing enhanced biodegradability (Ahmed et al., 2025; Gunawan et al., 2020). For instance, polyester polyols derived from algae oils have been successfully formulated into footwear-grade foams that degrade rapidly under composting and soil conditions, addressing the critical issue of plastic waste accumulation (Gunawan et al., 2020). Similarly, novel biodegradable foams such as PBAT/PBS blends have been tailored to meet the thermal and mechanical demands of shoe applications, offering improved shrinkage resistance and dimensional stability (Tian et al., 2024).

Sustainability considerations extend beyond material sourcing to end-of-life management. Traditional EVA and PU foams used in footwear often persist in the environment for centuries, while bio-based foams have demonstrated faster biodegradation under natural conditions (Zavodna et al., 2020). This property aligns with growing consumer and regulatory demands for circular economy solutions in the textile and footwear industries. The integration of bio-based foams not only reduces dependence on non-renewable petrochemicals but also supports the design of biodegradable shoes, marking a step forward in addressing the environmental challenges posed by fast fashion and high footwear turnover rates.

INSITE

INSITE is steering the footwear industry toward a more sustainable future with its development of bio-based polyurethane (PU) foam. Their plant based foams now incorporate up to 70% Susterra® propanediol, a bio-polyol derived from U.S. grown dent corn, which serves as an integral, reactive component rather than a filler, enhancing foam engineering and performance. The Susterra® feedstock stands out for its transparency, backed by third-party life cycle assessments (LCAs), relevance, emphasising tangible carbon emission reductions, and measurable agricultural metrics tracked via the Truterra® program. Performance wise, these bio-based foams achieve durability on par with and in some aspects superior to their petrochemical counterparts, including better elongation, resilience, and compression set, along with engineerability for precise physical properties.

<https://insiteinsoles.com>

EVOCO

Evoco's FATES™ Bio-Foam technology represents a groundbreaking advancement in sustainable footwear materials. Crafted as a range of high performance polyester polyurethane bio-foams, these formulations deliver up to an impressive 85% plant derived content while maintaining the cushioning, durability, and flex qualities essential for footwear applications.

Employing patented plant based chemistry, FATES™ substantially reduces greenhouse gas emissions by up to 70% compared to conventional petroleum derived PU foams, a fact supported by cradle-to-gate life cycle analyses and third party certifications. These foams are highly adaptable available in poured PU, low-density sheetstock for die-cutting or compression moulding, memory foam, and even TPU variants making them suitable for insoles, midsoles, and a wide spectrum of durable goods applications.

<https://evocoltd.com/bio-foam/>



TUNERA™

TUNERA™ is a 100% bio-based, plastic free foam engineered to deliver elite level compression and effortless rebound qualities that surpass traditional synthetic foams while maintaining lasting comfort.

Crafted from natural rubber, vegetable oil, minerals, and cork, it's designed for natural circularity made from nutrients and purpose built to safely return to the earth at the end of its life cycle.

TUNERA™ is said to offer durability and comfort retention better than conventional synthetics in applications ranging from footwear to yoga mats.

<https://nfw.earth/tunera>



5.3 BREWERS SPENT GRAIN (BSG) MATERIALS

Brewers' spent grain (BSG) is the largest by-product of beer production, comprising husks, residual endosperm, proteins and lignocellulosic fibre left after mashing. Because it is abundant, protein and fibre-rich, and geographically concentrated around breweries, BSG has become a prime feedstock for “valorisation” into higher-value materials rather than animal feed or disposal (Puligundla et al., 2021; Mainardis et al., 2024).

In next-generation “plant-based leather” systems, BSG's proteins and polysaccharides can be isolated, plasticised and cross-linked into sheets that are then finished to achieve leather like materials, with similar strength and abrasion resistance characteristics without animal collagen or petro-polyurethane backings. (Puligundla et al., 2021; Mainardis et al., 2024).

Technically, converting BSG into leather like sheets involves (i) fractionating spent grain to obtain protein and hemicellulose-rich streams; (ii) formulating these with benign plasticisers and cross-linkers to create coherent films; and (iii) laminating, embossing and coating to tune tear strength, flexibility, water uptake and surface aesthetics. This builds on a substantial literature around BSG processing (protein extraction, fibre modification, water sorption management) that informs durability and finish choices for two companies who are already utilising this technology ‘ARDA’ and ‘UNCAGED’ (Sanches et al., 2023; Mainardis et al., 2024). Beyond fashion, European projects are also exploring BSG-based polymers for technical textiles and automotive interiors, underscoring the pathway from brewery waste to functional, leather-adjacent biomaterials (Circular Economy Platform, 2024).

NEW GRAIN™ by ARDA

Arda Biomaterials has pioneered New Grain™, a revolutionary leather like material crafted entirely from upcycled brewer's and distiller's spent grain, a protein-rich byproduct traditionally used in low value cattle feed or biogas. Through their proprietary supramolecular chemistry, Arda transforms this plant derived protein into a high-performance, plastic free alternative that replicates the fibrous structure of animal leather. New Grain™ can be tailored in texture, thickness, and performance properties, making it suitable for applications across fashion, footwear, automotive, upholstery, and more. Though not yet commercially available, it has already been prototyped in luxury collaborations such as a snake-texture Millais bag with BEEN London in 2024 and a skull engraved cardholder for Beavertown Brewery, highlighting its potential to displace traditional leather at scale.

<https://arda.bio/materials-1>

ELEVATE by UNCAGED

UNCAGED's flagship material, known as ELEVATE, is a high-performance, animal-free alternative to traditional leather, ingeniously crafted from structural plant proteins, particularly grain proteins, fused with other bio-based elements to replicate the collagen scaffolding found in animal hides (UNCAGED Innovations, 2025a). This innovative biotech material is produced without animal-derived inputs, tanning chemicals, or plastics, setting a new standard for sustainable design in fashion, automotive, and home goods (UNCAGED Innovations, 2025a). Leveraging their proprietary BioFuze platform, UNCAGED achieves remarkable environmental efficiency. ELEVATE reportedly reduces greenhouse gas emissions by up to 95 %, cuts water usage by 89 % to 93 %, and slashes energy consumption by 71 % to 72 %, compared to conventional animal leather (Hyundai, 2023; Global AgInvesting, 2023). In doing so, UNCAGED delivers a luxurious, durable, and scalable leather substitute that aligns performance with sustainability.

<https://uncagedinnovations.com/material/>



5.4 Fish Skin materials

Fish skin has emerged as a new sustainable alternative to traditional leathers, particularly in footwear applications. Globally, fish processing generates vast amounts of waste, with skins often discarded despite their structural and aesthetic potential. Recent research highlights that fish skins, when processed into leather, display a uniform fibre arrangement that provides considerable tensile strength relative to their thinness, offering durability comparable to land animal hides (Isegbe, 2023; Lohay, 2023). This strength, combined with their unique natural textures, makes them suitable for high-wear products such as shoes.

From a sustainability perspective, fish leather provides a dual advantage: it utilises a by-product that would otherwise contribute to waste streams, and it avoids some of the environmentally damaging processes associated with conventional leather production. Traditional tanning of cattle hides often relies on chromium-based methods, which are linked to toxic pollution. In contrast, fish leather can be produced with less reliance on such chemicals, particularly as researchers experiment with vegetable tanning and water-based processing innovations (Isegbe, 2023; Palomino & Defeo, 2022). Additionally, the smaller size of fish skins encourages efficient, small-scale production models that can align with circular economy principles.

In footwear, fish leather has proven especially promising. Its non-slip surface, created by the scale pockets, enhances grip, a feature valued in shoe design (Lohay, 2023). Furthermore, its collagen rich composition contributes to flexibility and resilience, qualities essential for comfortable and long lasting footwear. Sports brands have already experimented with incorporating fish leather into collections, suggesting growing recognition of its aesthetic and performance attributes (Isegbe, 2023). The integration of digital printing and design innovation further expands its potential, enabling fish leather to compete not just as a sustainable material but also as a versatile one in contemporary design (Palomino & Defeo, 2022).

NOVA KAERU

Nova Kaeru's pirarucu (*Arapaima gigas*) fish skin material exemplifies sustainable and ethical innovation. Skillfully upcycled from food industry byproducts and processed via the brand's proprietary, organic "LIVE™" tanning method, free of heavy metals and chromes, it ensures compliance with rigorous IBAMA and CITES regulations while restoring biodiversity and supporting indigenous and riverside communities, having achieved an estimated +425 % increase in pirarucu populations (Global Green Solutions, 2024; MaterialDistrict, 2020).

Adding a revolutionary layer of functionality and creative potential, the patented Mousaikon Technology enables seamless welding of fish skins such as pirarucu, salmon, and even bovine or biomaterials such as beLEAF™ into expansive, continuous surfaces that remain as durable and visually striking as the original material. This innovation opens up applications across fashion, footwear, interiors, and architecture.

<https://novakaeru.com.br/en/>

ICTYOS TANNING

ICTYOS is a French eco-tannery founded in 2018 by Benjamin Malatrait, Gauthier Lefébure, and Emmanuel Fourault, marking the first new tannery in France for more than 40 years (La Maison des Startups LVMH, n.d.). The company specialises in transforming discarded fish skins from the food industry into high-end marine leather through a vegetable tanning process that uses renewable tannins such as mimosa, chestnut, and quebracho instead of harmful metals like chromium (Chemistry for Sustainability, 2024). This method results in durable, hypoallergenic leather that preserves natural fish scale patterns while producing a distinctive woody scent (ICTYOS, 2018).

Based in Lyon, ICTYOS supplies more than 1,000 clients across over 40 countries, with applications spanning fashion, watchmaking, footwear, automotive interiors, and design (Dealroom, 2025; Luxus+, 2023). Their signature lines include Squama® (salmon), NOVA® (sturgeon), and Naya® (sea bass).

By repurposing waste into premium materials, ICTYOS reduces both water use and carbon footprint compared with conventional tanning, strengthening its position as a sustainable alternative.

<https://www.ictyos.com/>

NORDIC FISH LEATHER TANNING

Nordic Fish Leather, based in Sauðárkróki, Iceland, is a pioneering tannery that transforms salmon and wolffish skins—typically regarded as waste by the food industry into high quality, durable leather (Lovia Collection blog, 2025; Nordic Fish Leather website, 2025).

The company produces both uncoated (natural, undyed or dyed) and transparent-finish fish leathers, maintaining the organic pigments or removing them entirely for custom coloration (Nordic Fish Leather website, 2025). Its tanning methods are examples of sustainable practice: powered entirely by renewable hydroelectricity and utilising geothermal hot-spring water, the process achieves minimal carbon emissions (Woden / WODEN A/S site, 2025).

<https://nordicfishleather.com>



5.5 GRAPE MATERIALS

Grape leather has emerged as an innovative response to the environmental challenges posed by the wine industry's waste streams, particularly grape marc, which consists of skins, seeds, and stalks left over after winemaking. Globally, between 7.58 and 11.3 million tonnes of grape marc are produced each year, with Europe contributing nearly half of this amount (Hoxha, Taherzadeh and Marangon, 2025). Improper disposal of this biomass can generate serious ecological issues due to its high organic carbon and phenolic content, but it is increasingly being reimaged as a valuable resource for bio-based products. By transforming grape marc into alternatives like grape leather, waste is diverted from landfills and repurposed into durable materials aligned with circular economy principles.

Companies such as VEGEA have pioneered this transformation, developing grape leather by combining grape marc with water-based polyurethane to create a flexible, soft, and durable material suitable for fashion, furniture, and automotive applications (VEGEA, n.d.). Their approach provides an alternative to petroleum-derived synthetics that dominate the market. Similarly, PLANET OF THE GRAPES has advanced its own grape leather initiative, emphasising local sourcing and small-scale production that ties material innovation back to regional viticulture (PLANET OF THE GRAPES, n.d.).

From a material science perspective, grape leather sits within the broader field of plant-based biomaterials, which face both promise and challenge. Studies show that while natural fibres and by-product-derived materials like Piñatex® or Desserto® offer renewable origins, their biodegradation performance is variable and often limited by the inclusion of polymers such as PU or PLA (Sardroudi et al., 2024).

In grape leather's case, the extent to which it achieves true biodegradability depends on its formulation, but its use of waste biomass nonetheless represents a step forward compared to fossil-fuel synthetics. As Ferreira, Apolinário and Forman (2023) note, designers must carefully assess both performance and end-of-life scenarios when integrating biomaterials, ensuring that sustainability claims are backed by life cycle considerations.

In short, grape leather demonstrates how waste valorisation can intersect with product innovation. By transforming a problematic residue into a material with functional performance, VEGEA and PLANET OF THE GRAPES showcase how circular design and bioeconomy principles can be woven directly into everyday products.

VEGEA®

VEGEA® is an Italian innovator in the realm of biomaterials, offering advanced coated fabrics rich in vegetal, renewable, and recycled components, primarily derived from grape production by-products, along with plant oils and agricultural fibres. The name "VEGEA" blends "VEG" (Vegan) and "GEA" (Mother Earth), reflecting the company's mission to develop sustainable alternatives to petroleum-based and animal-derived materials. Focused on fashion, footwear, furniture, packaging, and automotive sectors, VEGEA transforms agro-industrial biomass particularly grape leftovers from winemaking, into high-value, eco-conscious textiles. Their production ethos centres on socially responsible methods, bio-based polymers, and the valorisation of agricultural residues as innovative feedstocks.

<https://www.vegeacompany.com>

PLANET OF THE GRAPES

Planet of the Grapes is transforming grape marc (the skins, seeds, and stalks left after wine pressing) into a grape leather material. Sourced directly from nearby organic vineyards in Provence, the grape marc becomes a bio-PU blend material that is 84% bio-based, fully animal-free, EU REACH compliant, and produced via a lean supply chain to minimise carbon footprint, enhance traceability, and embrace a local, values-driven community. Rather than viewing grape marc as waste, the company reframes it as a co-product, amplifying its value through cooperation with winemakers who understand the terroir and share the vision of giving the marc a purposeful second life.

<https://planetofthegrapes.fr>



5.6 HEMP BASED MATERIAL

Hemp based leather has emerged as a promising material within the growing field of plant-based and vegan alternatives to animal leather. Research highlights that traditional bovine leather production is highly resource intensive, relying on chemical heavy tanning processes that generate significant emissions and hazardous waste. In contrast, hemp leather demonstrates a lower environmental impact across most categories of life cycle assessment (LCA). A study comparing hemp leather to bovine leather found that while hemp processing consumed more water, it outperformed bovine leather in nearly every other respect, including energy use, acidification potential, eutrophication potential, and global warming potential (Hultkrantz, 2018). Hemp is also a resilient crop, it grows rapidly with minimal inputs, requires little to no pesticides, and can thrive across a wide range of climates, further enhancing its appeal as a sustainable raw material (Hultkrantz, 2018).

The increasing demand for cruelty-free and eco-friendly materials has positioned hemp as part of a broader shift towards plant-based leathers. Unlike synthetic leather, which is largely petroleum derived, hemp based leather reduces reliance on fossil fuels while addressing concerns about biodegradability. At the same time, the wider vegan fashion movement, which embraces materials like hemp alongside cotton, jute, and bamboo, has gained momentum as consumers grow more conscious of both animal welfare and environmental sustainability (Choi and Lee, 2021).

From a sustainability perspective, hemp belongs to the group of bast fibres (plant fibres derived from stems) that have long been recognised for their biodegradability, strength, and versatility (Islam, Hossain and Covington, 2025). Hemp-based leather extends the utility of hemp beyond textiles, offering a material that can serve in footwear, bags, upholstery, and automotive interiors while reducing reliance on conventional leather. Although challenges remain such as scaling production and improving processing techniques, hemp based leather stands out as a material that could help bridge the gap between performance demands and ethical and ecological responsibility.

LOVR™ by REVOLTECH

LOVR™ is a high-performance, sustainable alternative to conventional leather, crafted from hemp residues to deliver a truly regenerative material. Engineered for circularity, it is both biodegradable and recyclable, allowing it to seamlessly re-enter the material loop or return to nature without leaving harmful traces. Hemp serves as the foundation of LOVR™, acting as a natural carbon sink, requiring minimal water, needing no pesticides, and improving soil health, while giving new life to what would otherwise be agricultural waste. Despite its organic origins, LOVR™ is tough, it boasts exceptional abrasion, heat, and tensile resistance, making it an ideal choice for durable and stylish footwear as well as textiles, automotive interiors, and accessories. Available in diverse finishes, from soft suede to embossed or perforated textures, LOVR™ enables designers to create everything from sleek sneakers to rugged boots with a smaller environmental footprint. Completing the picture, its carbon footprint is said to be relatively low, emitting 0.51 kg CO₂ per m².

<https://www.revoltech.com/lovr>



5.7 MYCELIUM MATERIALS

Mycelium based leather, crafted from the root-like network of fungi, has emerged as a promising bio-based substitute to leather. Mycelium offers natural strength, flexibility, and biodegradability due to its dense interwoven hyphal networks made of chitin, glucans, and proteins, allowing it to replicate the tactile and structural properties of animal leather (Raman et al., 2022; Amobonye et al., 2023).

Recent research has explored diverse cultivation and processing methods to enhance mycelium-based materials. Abdelkader and Gomaa (2025) demonstrated that *Talaromyces* sp. grown on irradiated eggplant peel waste can be transformed into flexible, leather-like sheets with tensile strengths of up to 8 MPa, while also valorising food waste streams. Wijayarathna et al. (2025) advanced this approach by developing multilayer fungal composites using *Rhizopus delemar* cultivated on bread waste and tanned with natural vegetable tannins such as Tara, Myrobalan, and Chestnut. These composites achieved tensile strengths comparable to conventional leather (up to 20.5 MPa) and sufficient flexibility for footwear prototypes. Meanwhile, research with brown-rot fungi has shown that hot pressing and plasticizer treatments can significantly enhance density, tensile strength, and tear resistance, aligning performance with traditional leather requirements (Raman et al., 2022). Patent landscape reviews further emphasize the industrial race to scale up mycelium-based leather, with efforts focused on optimising fungal strains, fermentation systems, and sustainable post-processing methods (Elsacker, Vandeloock & Peeters, 2023).

These scientific advances have inspired a wave of commercial innovation. Start-ups and material companies are now introducing mycelium leathers to the market. MycoWorks has launched Reishi™, a fine-tuned mycelium material aimed at luxury fashion and automotive applications. Bolt Threads, through its Mylo™ platform, collaborates with global brands to create mycelium-based footwear and accessories (Hyde, n.d.). Ephea has developed a mycelium material designed for performance and scalability in fashion and interior design applications (Ephea, n.d.). Similarly, Hyfé focuses on transforming food waste into mycelium-based materials and ingredients, while PureWay develops bio-based mycelium leather targeted at sustainable consumer products. Together, these innovations highlight the growing ecosystem of bio-fabricated leather, offering viable pathways for footwear, apparel, automotive interiors, and even architectural materials.

Although challenges remain, such as achieving consistent mechanical properties, replacing polyurethane (PU) coatings, and scaling production, the convergence of scientific research and industrial investment suggests that mycelium-based leather could become a mainstream material. Its ability to utilise agro-industrial byproducts, such as bread and vegetable waste, aligns with circular economy principles and supports global sustainability goals (Wijayarathna et al., 2025; Amobonye et al., 2023). In footwear especially, where durability, flexibility, and aesthetics are critical, mycelium-based leathers are moving closer to offering a low-carbon, cruelty-free alternative to both animal and synthetic options.

REISHI™ by MYCOWORKS

Reishi™, produced by MycoWorks, is an innovative biomaterial that combines the tactile luxury and durability of animal leather with significant sustainability advantages through its proprietary Fine Mycelium™ process (MycoWorks 2023a). The technology engineers' dense mycelial networks, resulting in high abrasion resistance, flexibility, and structural integrity, while maintaining hypoallergenic and fire-retardant qualities (ICFF 2023). Unlike many “vegan leathers” that depend heavily on polyurethane or PVC, Reishi™ contains less than 1% polymer content, making it both biodegradable and low impact (Williams et al. 2022). A peer-reviewed Life Cycle Assessment (LCA) found that its cradle-to-gate carbon footprint can be as low as 2.76 kg CO₂-eq per m², approximately 8% of bovine leather's footprint (Williams et al. 2022). Furthermore, across categories such as eutrophication, ecotoxicity, and human health, Reishi™ demonstrated 80–93% lower environmental impacts (Williams et al. 2022). These gains are amplified by MycoWorks' passive mycelium growth system, which avoids the carbon-intensive CO₂ supplementation required by other mushroom leather processes (Williams et al. 2022). With pilot and full-scale scenarios modelled, Reishi™ has proven scalable without compromising environmental performance, positioning it as a credible and commercially viable alternative in fashion, footwear, luxury, and automotive applications (Vogue Business 2021; MycoWorks 2023b).

<https://reishi.mycoworks.com>

MYLO™ by BOLT THREADS

Mylo™, developed by Bolt Threads, is an innovative leather alternative made from mycelium, the root-like underground network of fungi, cultivated in vertical farms using renewable energy. It delivers the softness, suppleness, and aesthetic of traditional leather while significantly reducing environmental impact (Bolt Threads, n.d.). Strategic collaborators, including adidas, Kering, lululemon, and Stella McCartney have formed the Mylo Consortium by investing to scale production and bring Mylo-infused products to market (Business Wire, 2020; FashionUnited, 2020). Real-world applications have included the Stella McCartney Falabella bag prototype (2018), her jet-black bustier and utility trousers (2021), the Frayme Mylo bag (2022), adidas' Stan Smith Mylo sneakers (2021), and lululemon yoga mats and gym bags (2022) (Stella McCartney, 2021; Vogue, 2021; Vogue Business, 2022; Bolt Threads, 2022). Despite nearing commercial scalability, Mylo production was paused in mid-2023 due to macroeconomic and funding challenges, though brand partners remain hopeful about its future (Vogue Business, 2023a; Vogue Business, 2023b).

<https://boltthreads.com/technology/mylo/>

EPHEA®

Ephea® is a groundbreaking mycelium-based biomaterial, not harvested, but grown from the fungal network beneath our feet, and reinvented for textile and fashion applications. Born in Italy through a proprietary fermentation process that ensures consistency, uniformity, and scale, Ephea panels are composed of 100% pure mycelium and offer a sensorial experience defined by sophisticated softness, lightweight suppleness, and unique textures.

Tailored to the demands of leather goods, accessories, and ready-to-wear apparel, the material demonstrates proven physical integrity, durability, and performance suitable for everyday items. Crafted with sustainability at its core, Ephea is produced using low-energy, low-water, low-land-use methods, is cruelty-free, highly traceable, and dramatically reduces CO₂ emissions compared to conventional leather.

<https://ephea.bio/product/>

HYDEFY

Hydefy's groundbreaking leather alternative is a high-performance, fungi-based biomaterial developed through nature inspired science and sustainably engineered technology. Rooted in NASA-backed research conducted at Yellowstone National Park, Hydefy leverages proprietary fermentation techniques that dramatically reduce water, land, and energy use compared to conventional materials. The result is a versatile, eco-friendly textile offering both aesthetic appeal and robust functionality, already showcased in luxury fashion through Stella McCartney's Stella Ryder crossbody bag unveiled on the Spring/Summer 2025 runway.

<https://www.hydefy.com>

GANO™ by PUREWAY

Pureway's proprietary mycelium-based material, Gano™, represents an innovative integration of biotechnology and sustainable design. Through a controlled bioengineering process, mycelium is cultivated into single sheets that preserve its natural growth patterns, producing a material with a texture and aesthetic comparable to conventional leather (Pureway Biotechnology, 2025a). In terms of potential applications, Gano™ can be employed across diverse design sectors, including fashion accessories, footwear, upholstery and interior elements, offering both functional flexibility and distinctive surface qualities (Pureway Biotechnology, 2025b; Andres & Colour Compass, 2025).

A central benefit of Gano™ lies in its environmental performance. Unlike traditional leather, which relies on resource intensive livestock farming and often involves toxic tanning processes, Gano™ reduces ecological impact by eliminating these practices (Pureway Biotechnology, 2025a). Furthermore, mycelium-based materials are generally biodegradable and may be compostable, while production methods typically utilise agricultural waste substrates and require comparatively low energy inputs (Fibre2Fashion, 2021; Wikipedia, 2025).

<https://purewaybio.com/>



5.8 OTHER PLANT BASED LEATHER MATERIALS

Fruit-based leathers have gained significant attention in recent years. Mango waste, for instance, has been successfully repurposed into vegan leather, providing not only a high-value product but also a solution to fruit waste management. Mango-based vegan leathers have been found to be durable, multifunctional, and attractive to green consumers, particularly in fashion accessories such as handbags (Maitree et al., 2024). Similarly, orange peel waste has been investigated as a raw material for leather-like composites, showing promising mechanical properties such as tensile strength and tear resistance. These findings highlight the potential of citrus by-products as viable inputs for sustainable material innovation (Rimantho et al., 2024).

Vegetable-based leathers also include developments from cactus (Desserto®) and pineapple leaves (Piñatex®). These materials demonstrate versatility across industries such as automotive interiors, footwear, and apparel (Malabadi et al., 2025). Olive-based leathers, derived from olive tree bark and waste, represent another promising innovation. They reflect a growing trend of using agricultural by-products from staple crops in Mediterranean regions to generate eco-friendly, durable, and cruelty-free fashion materials (Malabadi et al., 2025).

Overall, plant-based leathers offer significant environmental benefits, reducing reliance on animal agriculture and fossil-fuel-derived synthetics. They are often biodegradable, hypoallergenic, and have lower water and land footprints compared to conventional leather. However, challenges remain regarding cost, scalability, and availability, which currently limit their widespread adoption. Nevertheless, as consumer demand for ethical and sustainable fashion grows, fruit and vegetable leathers including mango, orange, and olive leather, are likely to become increasingly central to future material innovation (Tran Minh & Ngo Ngan, 2021; Maitree et al., 2024).

OLEATEX

Oleatex is a vegan, plant-based material made largely from bio-waste from the olive oil industry. Comprising up to about 90% bio-content, it transforms agricultural by-products, olive pits, leaf material (olive tree bio-waste) into a material suitable for textile and manufacturing applications. It aims to bridge sustainability and performance, offering an alternative to leather or synthetic leather that relies heavily on fossil-derived polymers, while supporting circularity in agriculture. The development of Oleatex underscores careful design not only for environmental benefit (reduced waste, lower carbon footprint) but also adaptability, so it can be used in fashion, footwear, upholstery, and other product areas requiring durability, texture, and visual appeal.

<https://oleatex.com>

AAMTI GREEN AND FRUITLEATHER ROTTERDAM

Aamati Green and Fruit Leather Rotterdam are two pioneering efforts to turn fruit waste, especially mango residues, into sustainable, leather-like materials. Aamati produces a mango-based “fruit leather” alternative using mango agro-waste combined with bio-polymers; its products are biodegradable, cruelty-free, and designed to replace both traditional animal leather and synthetic vegan leathers that rely on plastics like PU or PVC.

<https://www.aamatigreen.com>

Fruit Leather works similarly from the Netherlands: it collects discarded or unsold fruit (often mangoes) from sources such as the port of Rotterdam, then processes the fruit pulp through cooking, drying, and finishing steps to produce sheets that mimic leather.

These materials are being applied in fashion accessories, footwear, upholstery and furnishings, and represent a way both to reduce food waste and to lessen the environmental impact of the conventional leather industry.

<https://fruitleather.nl>

PINEATEX® BY ANANAS ANAM

Pineapple leather, as developed by Ananas Anam under the trade name Piñatex®, is an innovative, plant-based alternative to conventional leather. It is made using fibres from pineapple leaves, an agricultural by-product that would usually be thrown away or burnt, which helps reduce waste and the environmental cost associated with pineapple farming.

The leaves are processed to extract the long cellulose fibres, which are then felted into a non-woven textile substrate. To give Piñatex durability, flexibility, and the feel of leather, the material is combined with PLA (polylactic acid, a corn-based bioplastic) and coated with resins.

In terms of sustainability, Piñatex offers several advantages: it doesn't require additional land, water, or fertilisers (since it uses waste material), it helps reduce CO₂ emissions by preventing the burning of pineapple leaf waste, and the processing avoids many of the toxic chemicals used in tanning animal leather.

Performance-wise, Piñatex is said to pass many of the technical tests required for footwear, bags and upholstery: it is flexible, strong in stitching, has good abrasion resistance, and it weighs much less than traditional leather. However, there are some trade-offs, because it has coatings and resin layers, full biodegradability depends on the exact finish used; also, its texture and care requirements differ from animal hide.

<https://www.ananas-anam.com>

INNOVERA

INNOVERA™ (formerly BIO-VERA®), by Modern Meadow, is a 100% animal-free leather-alternative material that aims to replicate the look, feel and performance of traditional collagen based leather using bio-design technologies. It is made from a blend of plant-based proteins, biopolymers, and recycled rubber (from post-consumer tyre waste) via a chemical recycling route in collaboration with BASF, achieving over 80% renewable carbon content.

INNOVERA comes as a “Dry White” semi-finished product, meaning it bypasses many of the resource-intensive early steps in leather processing. Because of this format, it does not require special cold storage or stabilisation and can be integrated into traditional post-tanning and finishing workflows, helping reduce environmental impact.

The material is offered in various textures, colours, finishes and haptics (e.g. full grain, aniline, croc, suede, perforated, foil), and is meant to deliver the aesthetics, strength (claimed to be twice as strong as natural materials in use), and sensory qualities that brands expect from leather. Its production capacity is at scale (~500,000 m²/year), so it is positioned not just as a novelty, but a practical alternative for industries in fashion and footwear.

<https://innovera-world.com/innovera>



5.9 Adhesives - Current and Alternatives

5.9.1 Current Adhesives in Footwear

The footwear industry traditionally relies on solvent-based polyurethane (PU) and neoprene (chloroprene rubber) adhesives for bonding leather, rubber, and synthetic materials due to their strong and versatile bonding properties (Simões et al., 2024; SERMA, 2024). However, these adhesives are significant sources of volatile organic compounds (VOCs), such as toluene and acetone, which contribute to photochemical smog and cause respiratory and neurological health issues among workers (Simões et al., 2024). PU systems are also based on isocyanates, which are toxic and associated with occupational asthma and carcinogenic potential (Simões et al., 2024). Despite their high performance, these environmental and safety drawbacks have prompted a shift toward more sustainable adhesive systems.

According to H.B. Fuller (2025), adhesive selection in footwear must balance material compatibility, durability, and processing conditions, but sustainability is increasingly shaping formulation trends. Current industrial innovations include microencapsulated polyurethane (PUMC) adhesives, where the isocyanate component is encapsulated to reduce worker exposure and extend product shelf life while maintaining strong bond performance (Simões et al., 2024). Life cycle assessment (LCA) data shows that, although microencapsulation adds some manufacturing complexity, optimising microcapsule production and energy efficiency can bring its environmental footprint close to or even below that of conventional PU adhesives (Simões et al., 2024).

5.9.2 Water-Based and Hot-Melt Adhesives

Water-based polyurethane (WPU) and acrylic adhesives are increasingly adopted as safer alternatives to solvent-based systems. These adhesives eliminate most VOC emissions and allow easy clean-up, improving worker safety and reducing regulatory concerns (H.B. Fuller, 2025). However, WPU can require longer drying times and careful surface preparation to achieve adhesion comparable to solvent-based adhesives (SERMA, 2024). Their environmental benefits are substantial—LCAs have shown lower greenhouse gas emissions and reduced human toxicity potential compared to solvent-based adhesives (Maciel et al., 2017, cited in Simões et al., 2024).

Reactive polyurethane hot melt adhesives (HMPUR) represent another solvent-free solution widely used in modern footwear. These adhesives cure by moisture and provide high flexibility, thermal resistance, and durability. When synthesized using bio-based polyols from vegetable oils such as soybean, castor, and linseed, HMPUR adhesives offer comparable mechanical performance while improving biodegradability and reducing reliance on fossil carbon (Blasco et al., 2022). Studies show that leather-rubber joints bonded with bio-based HMPUR meet all mechanical quality standards required in footwear, achieving peel strengths similar to petroleum-based systems (Blasco et al., 2022).

5.9.3 Alternative Bio-Based Adhesives

Sustainable alternatives are also emerging through the use of bio-polyurethane adhesives (bio-PUAs) derived from renewable vegetable oils. These adhesives retain the desirable elasticity and strength of traditional PU systems but emit significantly fewer VOCs and have a reduced carbon footprint (Maulana et al., 2024). Vegetable oil-based adhesives, developed from feedstocks like soybean, castor, and linseed oils, exploit triglyceride modification to produce polyols for PU synthesis, allowing them to act as high-performance yet biodegradable bonding agents for footwear (Maulana et al., 2024). Their production also supports circular economy principles and rural economic development through the use of renewable agricultural inputs.

Moreover, advanced surface treatments such as plasma activation are being explored to enhance adhesion between rubbers and water-based or bio-based adhesives. For instance, Múgica-Vidal et al. (2021) demonstrated that atmospheric pressure plasma treatments can replace harmful halogenation processes used to prepare styrene-butadiene rubber (SBR) outsoles, improving bond strength by 10–12 times while eliminating chlorine-based residues. This innovation represents a cleaner and more energy-efficient surface modification strategy compatible with eco-friendly adhesive systems.

5.9.4 Environmental Concerns and Improvements

Environmental challenges in footwear adhesives primarily concern toxic emissions, energy use, and waste generation. Conventional PU and solvent-based adhesives are major contributors to VOC emissions, over 12,000 tons annually in the U.S. (Maulana et al., 2024), and depend on non-renewable petrochemical resources. Efforts to mitigate these impacts focus on:

- Replacing solvents with water or 100 % solids systems to eliminate VOCs (H.B. Fuller, 2025).
- Substituting petrochemical polyols with bio-based alternatives to lower carbon intensity (Blasco et al., 2022; Maulana et al., 2024).
- Implementing microencapsulation to reduce isocyanate exposure and extend adhesive life (Simões et al., 2024).
- Adopting plasma and UV treatments to improve surface activation without hazardous chemicals (Múgica-Vidal et al., 2021).
- Utilising renewable energy and optimising production efficiency, which can make new adhesive systems environmentally comparable to traditional ones (Simões et al., 2024).

Collectively, these advances illustrate a clear industrial transition toward safer, low-emission, and circular adhesive technologies that maintain high performance for footwear manufacturing.

5.10 Summary of Alternative Bio-based Materials and Adhesives

Overall, alternative materials for footwear demonstrate clear environmental benefits over conventional leather and petroleum-based synthetics. They reduce greenhouse gas emissions, valorise waste streams, and align with circular economy principles. Among them, mycelium and hemp-based materials show the strongest potential for balancing sustainability, durability, and scalability. Agricultural waste derived materials (grape, BSG, fruit leathers) provide powerful waste reduction pathways, though they often face technical and perception barriers.

For adhesives, bio-based polyurethane and water-based acrylics are emerging as viable substitutes for VOC-heavy solvent systems. Together, these advances enable the design of footwear that performs well in demanding outdoor conditions while drastically cutting its carbon and chemical footprint.

The transition to these alternatives is unlikely to be uniform. Rather, a portfolio approach, combining algae foams for midsoles, mycelium and waste derived leathers for uppers will be necessary to reduce the footwear industry's environmental impact. Investments in scaling, certification, and consumer education will be critical to their broader acceptance. In time, these innovations show promise to move from niche luxury or experimental products to mainstream solutions that meaningfully reduce the sector's carbon and waste footprint.

Table 2: Postives, Negatives and Environmental Benefits of New Alternative Bio-based Materials

Alternative Material Type	Potential Replacement For	Positives	Negatives / Challenges	Environmental Benefits
Algae-based	Upper materials and Mid-soles	Renewable, biodegradable, antimicrobial, replaces petroleum foams	Limited durability data, scaling issues	Reduces microplastics, purifies water, low land use
Bio-based foams	Mid-soles and Outer Soles	Comparable/better performance than PU, biodegradable, lower CO ₂	Industrial scaling, compostability varies	Up to 70% CO ₂ savings, reduced petrochemical reliance
Fish skin leather	Upper materials	Strong, flexible, upcycled waste, natural grip, unique aesthetics	Small size, irregular supply, consumer perception	Diverts food waste, less chemical-intensive
Brewers' spent grain	Upper materials	Abundant feedstock, leather-like properties, protein/fibre durability	Requires binders (PU), not fully biodegradable	Upcycles brewery waste, cuts emissions
Grape leather	Upper materials	Waste valorisation, durable, flexible, vegan-friendly	Often mixed with PU, biodegradability limited	Diverts millions of tonnes of grape marc waste
Hemp leather	Upper materials	Low-input crop, strong, biodegradable, soil regenerating	Higher water use than bovine leather, scaling challenges	Carbon sequestration, cruelty-free, fossil-free
Mycelium leather	Upper materials	Low CO ₂ , biodegradable, scalable prototypes, strong durability	Coatings reduce biodegradability, cost, scaling issues	Up to 90% lower footprint than bovine leather
Other plant-based leathers	Upper materials	Uses waste (pineapple, cactus, mango, orange, olive), cruelty-free	Requires resins/coatings, limited durability, higher cost	Reduces waste, avoids livestock farming

Table 3: Postives, Negatives and Environmental Benefits of Adhesives

Type	Positives	Negatives / Challenges	Environmental Benefits
Solvent-based PU & Neoprene	Strong bonding, widely compatible with materials	High VOC emissions, toxic isocyanates, worker health risks	None – major contributor to air pollution
Water-based PU & Acrylic	Low VOCs, safer for workers, lower carbon footprint	Longer drying time, surface prep needed	Major reduction in VOCs and toxicity
Reactive Hot-Melt PU (HMPUR)	Solvent-free, high flexibility and durability	Moisture-sensitive, higher cost	Reduces solvent use and fossil dependency
Bio-based PU Adhesives	Renewable feedstocks (soy, castor oils), strong bonds	Early-stage commercialisation, variable curing	Biodegradable, lower carbon footprint
Microencapsulated PU Systems	Reduced worker exposure to isocyanates, longer shelf life	Added manufacturing complexity	Lower toxicity, improved process safety
Plasma/UV Surface Treatment	Eliminates halogenation, enhances bond strength	Equipment costs	Replaces toxic surface prep processes

5.11 Life Cycle Assessment (LCA) of New Alternative Materials

All of the new alternative materials for footwear discussed in this report currently lack robust and directly comparable life cycle assessment (LCA) data. In many cases, no LCA information is available yet, while in other cases the data provided varies in scope and methodology, making meaningful comparison across materials difficult. As a result, any existing LCA related information cannot be consistently evaluated within the main body of the report. To maintain clarity and analytical integrity, the available LCA details, where they exist, are therefore presented separately in the appendix for reference rather than comparative assessment.



6. DISCUSSION AND CONCLUSION

6.1 Discussion

The challenges between the outdoor industry's demand for high-performance footwear materials and the growing urgency to reduce environmental impacts is clear. Conventional materials such as leather, synthetic polymers, EVA, and rubber continue to dominate due to their durability, functionality, and market familiarity. However, their production and end-of-life management present significant sustainability challenges, including high carbon emissions, chemical pollution, landfill persistence, and limited recycling potential.

Alternative materials discussed in this report, from algae-based foams and mycelium leathers to recycled synthetics, hemp, and agricultural by-product composites, demonstrate clear potential to address these issues. Many of these materials are derived from renewable sources, valorise industrial waste streams, and offer enhanced circularity through biodegradability or recyclability. Notably, innovations such as bio-foams, fish leather, and grape or brewer's grain leathers illustrate how by-products can be upcycled into durable, premium products that align with circular economy principles.

Despite these advances, several challenges remain. First, scalability and cost competitiveness continue to restrict widespread adoption, with many biomaterials still in pilot or niche applications. Second, there may be performance trade-offs such as durability, abrasion resistance, water repellence, or mechanical strength of established synthetics and animal leather. Third, supply chain transparency and certification are essential to ensure credibility, avoid greenwashing, and provide consumers with verifiable sustainability claims.

The question the outdoor footwear industry should also consider is, should the path toward sustainability prioritise recycled synthetics or alternative bio-based materials? Both approaches aim to reduce the sector's dependence on virgin petrochemicals and animal-derived inputs, yet they represent fundamentally different strategies.

Recycled materials, particularly recycled polyester (rPET), nylon, EVA, and rubber, offer near-term advantages because they integrate smoothly into existing manufacturing systems. They help close material loops, reduce reliance on virgin feedstocks, and are increasingly backed by scalable supply chains through initiatives such as Accelerating Circularity and industrial chemical recycling technologies. However, the extent of their sustainability depends heavily on input sources and recycling methods. Much of the current rPET supply still originates from bottles rather than post-consumer textiles, and chemical recycling of nylon and EVA remains energy intensive. Moreover, recycling does not eliminate microplastic pollution or the persistence of these polymers at end-of-life, which raises doubts about their long-term compatibility with circular economy principles.

In contrast, bio-based and next-generation materials, including those mentioned in the report, shift the paradigm toward renewable and biodegradable inputs. These innovations may offer a lower carbon footprint and greater alignment with regenerative systems, yet face ongoing challenges in scalability, performance consistency, and cost. Many still rely on small-batch production or partial blends with synthetic binders to achieve durability, which complicates claims of full biodegradability.

The debate, therefore, is not simply about which material is “better,” but rather which strategy offers the most credible and resilient path toward systemic sustainability. Recycled synthetics may serve as an essential transitional phase, leveraging existing infrastructure while bio-based materials mature. However, overreliance on recycling fossil-based polymers risks delaying the broader shift toward renewable, circular, and biodegradable material ecosystems. The outdoor industry's long-term innovation agenda will need to balance these dual priorities, scaling recycling now, while investing in the research and commercialisation of next-generation biomaterials for the future.

6.2 Conclusion

As the outdoor footwear industry confronts rising environmental and regulatory pressures, it must decide whether enhancing recycling systems or accelerating the adoption of bio-based alternatives represents the most effective sustainability route. Recycled synthetics provide a pragmatic short-term solution, reducing resource extraction and supporting circularity within familiar production frameworks. Yet, they remain tied to fossil-based chemistry and may only partially address the sector's broader ecological footprint.

Bio-based and waste-derived materials, meanwhile, embody a more transformative shift toward renewable, biodegradable, and regenerative systems. Their potential to decouple performance footwear from petrochemical dependence positions them as a long-term solution, albeit one requiring further innovation, infrastructure development, and cross-industry collaboration to achieve true scale and durability parity.

Ultimately, the question is not whether to choose recycled or bio-based materials exclusively, but how to design a strategic progression from one to the other. The outdoor industry should adopt a dual-track approach: scaling high-quality recycling to reduce immediate impacts while simultaneously investing in biomaterial R&D, pilot testing, and supply-chain partnerships. By embracing both transitional and transformative solutions, the sector can move toward genuine material circularity, ensuring performance, sustainability, and resilience coexist in the next generation of outdoor footwear.

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The EOG gratefully acknowledges the use of the following images and resources that appear in this report. Images were sourced primarily from Unsplash, the BBC, and the Caswell Adhesives website.

Images courtesy of:

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Additional materials:

- Adhesive image – Caswell Adhesives website - <https://www.caswell-adhesives.co.uk>
- Brewers spent grain – BBC news article - <https://www.bbc.co.uk/future/article/20250206-how-brewers-spent-grain-is-being-turned-into-vegan-barley-milk-leather-and-cakes>
- Tannery dyeing pits, Medina, Morocco - <https://www.artisansofleisure.com/luxury-travel-blog/2021/11/visiting-tanneries-in-fez-morocco/>

APPENDIX.01

Alternative Material	LCA information available	Contact information
MATTR™	Was meant to be available middle of 2025	info@revoltech.com
VEERAH	Not publicly available	help@veerah.com
INSITE	Available on request	sbobbett@insiteinsoles.com
EVOCO	See Appendix.02	ALeonard@evocoltd.com
TUNERA™	Not publicly available	https://nfw.earth/contact
New Grain™	Not publicly available	https://arda.bio/contact-form
ELEVATE	See Appendix.03	https://uncagedinnovations.com/contact/
NOVA KAERU	Not publicly available	contato@kaeru.com.br

APPENDIX.01

Alternative Material	LCA information available	Contact information
ICTYOS	See Appendix.04	e.fourault@ictyos.com
NORDID FISH LEATHER	Available on request	hlynur@nordicfishleather.com
VEGEA	Available on request	v.longobardo@vegeacompany.com
PLANET OF THE GRAPES	Available on request	sam@planetofthegrapes.fr
LOVR™	Not publicly available	info@revoltech.com
REISHI™	See references: https://enveurope.springeropen.com/articles/10.1186/s12302-022-00689-x	n/a
MYLO™	Not publicly available	https://boltthreads.com/contact/
EPHEA®	Not publicly available	https://ephea.bio/contact-collab/

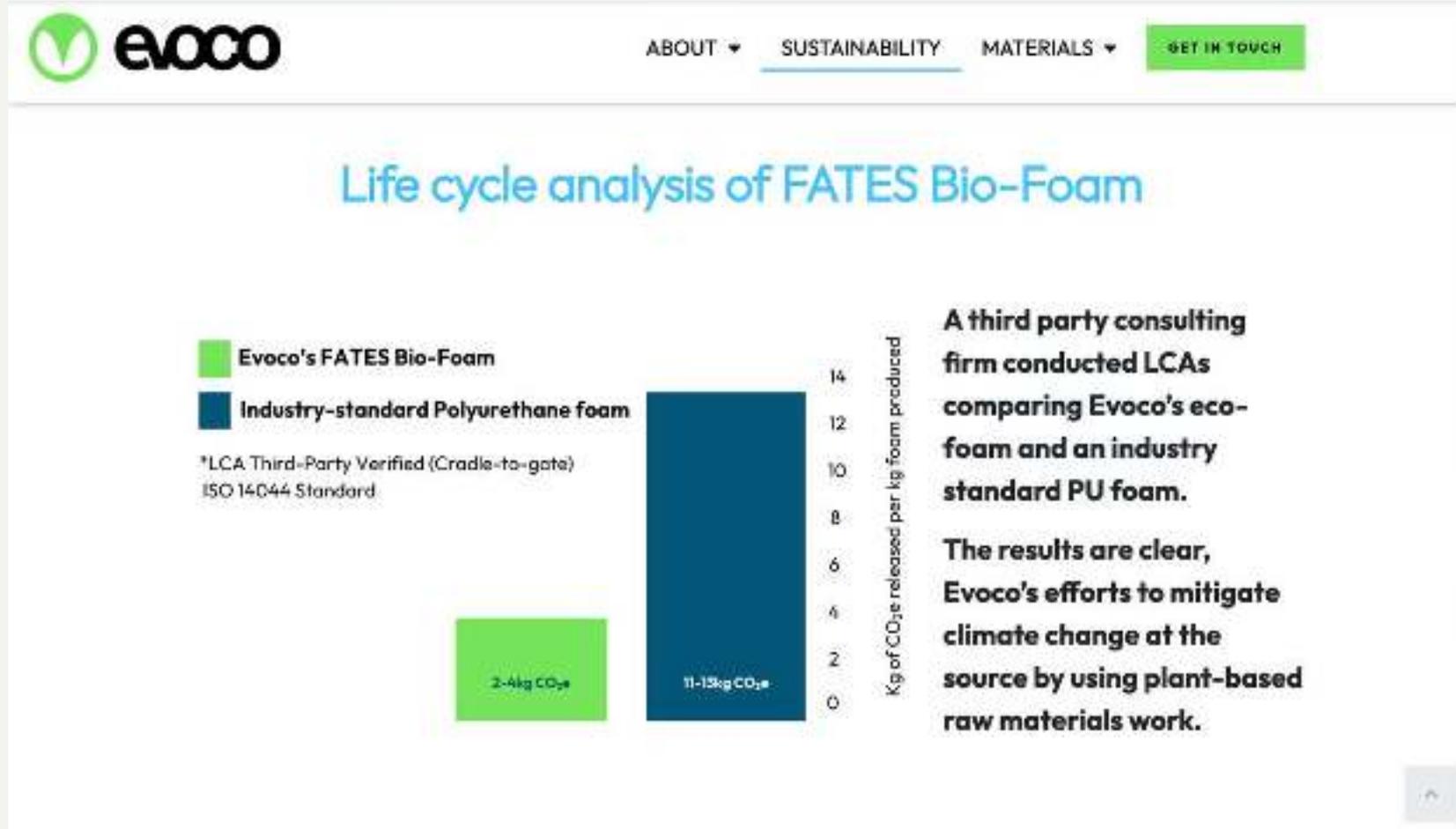
APPENDIX.01

Alternative Material	LCA information available	Contact information
HYDEPHY	Not publicly available	hello@hydefy.com
GANO™	Not publicly available	general@purewaybio.com
OLEATEX	Not publicly available	https://oleatex.com/contact
AAMATI	Not publicly available	Pratik@aamatigreen.com
FRUIT LEATHER	Not publicly available	hugo@fruitleather.nl
ANANAS ANAM	Not publicly available	info@ananas-anam.com
INNOVERA	Available on request	fposenato@modernmeadow.com

APPENDIX.02

EVOCO - LIFE CYCLE ANALYSIS

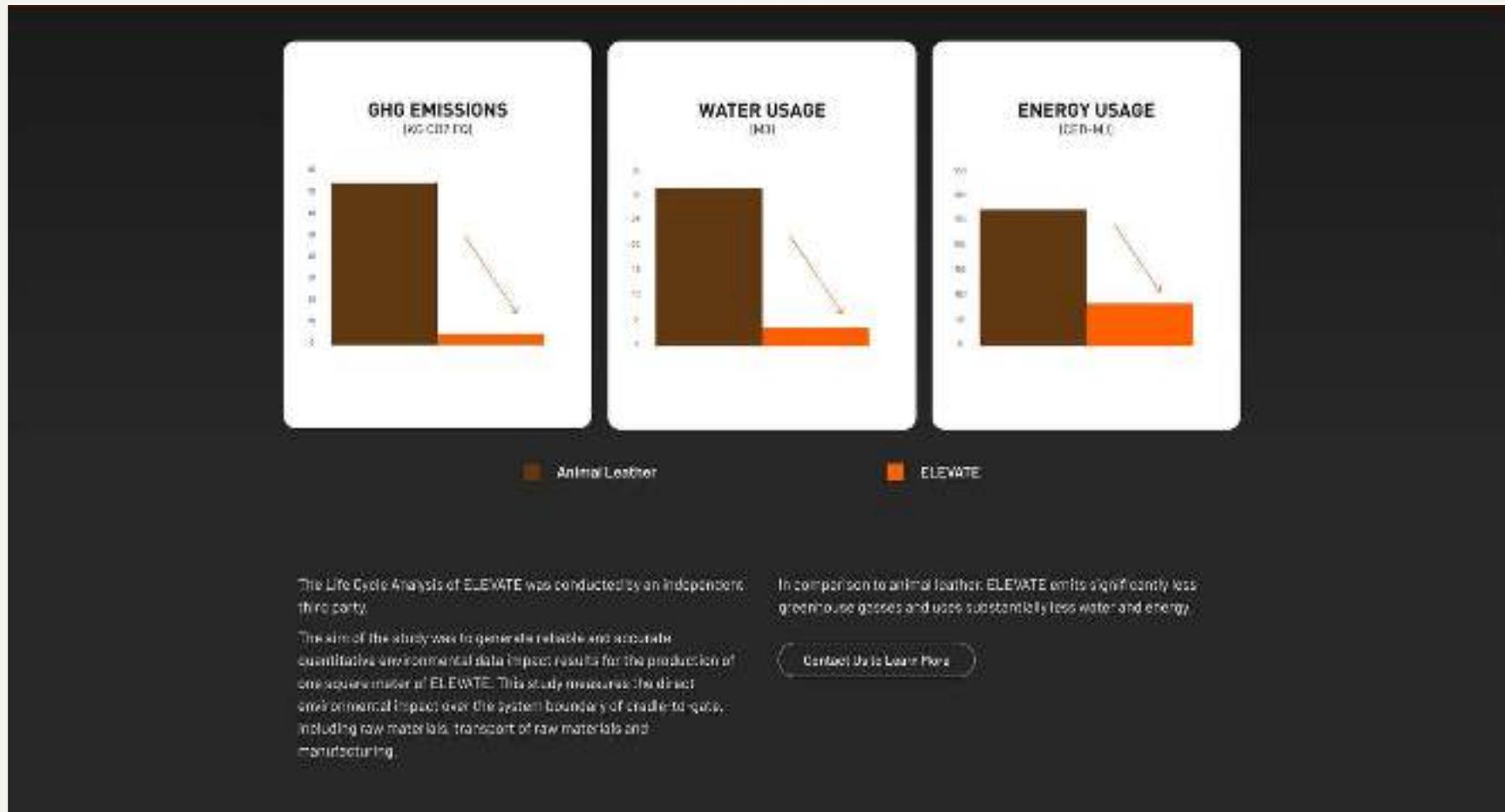
Available from - <https://evocoltd.com/sustainability/>



APPENDIX.03

ELEVATE - LIFE CYCLE ANALYSIS

Available from - <https://uncagedinnovations.com/impact/>



APPENDIX.04

ICTYOS - LIFE CYCLE ANALYSIS



APPENDIX.04

ICTYOS - LIFE CYCLE ANALYSIS

