

# Report on benchmarking and technology watch

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Author: CITEVE

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## Contributors

Contributors	Ana Filipa Costa, Margarida Fernandes, Ashly Rocha, Catarina Guise, Augusta Silva, Jéssica Antunes
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## List of Abbreviations

Acronyms	Description
AI	Artificial intelligence
BHET	Bis(2-hydroxyethyl) terephthalate
BPA	Bisphenol A
CO	Cotton
D	Deliverable
DIN	Deutsches Institut für Normung
DMT	Dimethyl terephthalate
EVA	Ethylene-vinyl acetate
M	Month
MEG	Mono-ethylene glycol
PDO	1,3-Propanediol
PE	Polyethylene
PEF	Polyethylene furanoate
PES	Polyester
PET	Polyethylene terephthalate
PHA	Poly-hydroxyalkanoate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid
PP	Polypropylene
PTA	Purified terephthalic acid
PTT	Polytrimethylene terephthalate
PU	Polyurethane
R&D	Research and development
scl-PHA	Short chain length PHA
T	Task
TPA	Terephthalic acid
<b>W2BC</b>	<b>Waste2BioComp</b>
WP	Work package
yr	Year

# 1. Introduction

This report represents the final version of the Report on benchmarking and technology watch. It describes **Waste2BioComp (W2BC)** strategic benchmark and technology watch. Benchmarking strategic tool assists in the achievement of excellence, enabling improvement by borrowing and adapting the successful ideas and practices of organizations while avoiding unproven or problematic strategies.

The main objective of WP7 ("Dissemination, Communication, Training, Exploitation, and Innovation Management") is to maximize the project's impact, by:

- ensuring effective communication and outreach of the project's activities and results to the identified target groups;
- dissemination of **W2BC** by raising awareness about the project's results and making them available to the multiple stakeholders;
- providing the tools and developing the skills needed for the implementation of biomaterial-based manufacturing activities (training);
- developing the project's exploitation strategy, realized by market analyses, benchmarking and technology watch, business models and business plans for commercialization.

As part of the **W2BC** consortium plan for exploitation and dissemination of results, this WP also seeks to develop a set of guidelines for the commercialization of the project outcomes, which are being adapted by each partner according to the specific requirements of each partner country. The task (T7.5 Benchmarking, Business plans and exploitation strategy for the bio-based materials) focuses on the identification of the different aspects required to define the business model and plan. In the proposal, an initial Business Plan and Business Model was outlined. However, a more detailed and continuous analysis is necessary to answer to the demands and evolution of both the market and the technology.

To complement this analysis, a Product Benchmarking was performed, to analyse all the possible limitations and weakness of the innovative products under development. Thus, a Benchmarking study was performed in **W2BC** with the main objective of comparing the innovative bio-based products and technologies developed with the current commercial solutions available at the market, namely:

- The shoe soles and insoles obtained by compounding and foaming will be compared with commercial fossil-based ones, namely EVA based ones from partner NORA;
- The plastic films/packaging obtained by blown extrusion, thermoforming and injection moulding will be compared with commercial fossil-based ones, namely PES and PE based ones from partner PROPAGROUP;
- The textiles with PHA coatings for technical textiles obtained by spray, or knife-coating will be compared with fossil-based technical textiles from partner RIOPELE;
- The different printed substrates obtained by inkjet printing with bio-based inks will be compared with similar substrates printed with fossil-based inks.

Also, the optimized production processes (chemical and biogenesis) for the PHAs will also be compared with current used methods, to indicate their commercial potential.

By comparing the results and processes of those studied (the commercial "targets") to one's own results and processes, the consortium learned how well the targets perform and, more importantly, the business processes that explain why they can be successful.

## 2. Benchmarking and technology watch

In this report a preliminary Product Benchmarking is presented, which aims to analyse the possible limitations and weaknesses of the innovative products under development, that may influence the outcomes of the project and/or the exploitation of its results.

It aims to align business opportunities with technical and research activities, through continuous market and patent watch activity (this last done under Task 7.4 and presented in deliverable D7.3). The current report compares the innovative smart manufacturing technologies of bio-based materials with current commercial solutions available on the market.

### 2.1 Bio-based inks & inkjet printing

Up till M12 of the project (May 2023), no inks for inkjet printing with bio-based pigments or dyes were found in the market. However, in the last ITMA'2023 (8-14 June) Milan, Italy, the leading global sourcing exhibition dedicated to the latest textile and garment technologies and solutions, one textile digital printing company, Torrecid (Spain), presented four digital textile pigment printing inks (cyan, magenta, yellow and black) based on natural coloration. These inks are incorporated with a synthetic binder. The supplier suggests carrying out a pre-treatment by padding, to increase the colour intensity as well as to avoid the spread of the printing design, and to perform a post-treatment by padding, to increase the colour fastness to washing, rubbing, etc.

Other alternative bio-based pigments found on the market, with the potential to be used in the production of digital printing bio inks (but not applied so far, to the best of our knowledge), include:

- Red fungal fermentation pigment from CHROMOLOGICS.<sup>1</sup> Sustainly.Red® has already been tested in textile applications, namely digital and traditional printing, looking for a natural and sustainable red colour to substitute artificial dyes;
- Microbial and enzymatic indigo pigment from Huue,<sup>2</sup> who creates microbes that mirror nature's process and consume sugar to enzymatically produce the dye;
- Bacterial dyes from Vienna Textile Lab.<sup>3</sup> Natural textiles (originating from plants and animals), as well as synthetic textile fibres, have been successfully dyed with these dyes, but they are not commercially available yet;
- Bacterial pigment extract from Faber Futures.<sup>4</sup> It consists in a blue pigment biologically derived from *Streptomyces coelicolor*. Faber Futures and Ginkgo Bioworks worked together to create a pigment extract of *S. coelicolor* to donate to the Forbes Pigment Collection, with potential applications in textile dyeing and printing;
- Water based black ink (AIR-INK®), made from carbon emissions, from Graviky;<sup>5</sup>
- Water-based dispersion black pigment derived from wood waste, from Nature Coatings, made with pre-consumer industrial wood waste from the lumber, paper, furniture and flooring industries. Some traditional printing applications are already available in the market.<sup>6</sup>
- Biogenic pigments from chitin and other bio-based dyes, developed by Fraunhofer IPA and the University of Paderborn, together with industrial partner Siegwark Druckfarben, under the "Crustacea chitin-based colour pigments (crusty pigments)" project.<sup>7</sup> The "Crusty Pigments" were developed in a pilot plant scale and are ideal for applications in areas where printing inks must be handled sensitively, e.g., in the production of food, cosmetics and pharmaceuticals packaging, as well as for interior design or textiles.

<sup>1</sup> <https://www.chromologics.com/>

<sup>2</sup> <https://www.huue.bio/>

<sup>3</sup> <https://www.viennatextilelab.at/>

<sup>4</sup> <https://faberfutures.com/>

<sup>5</sup> <https://www.graviky.com/>

<sup>6</sup> <https://www.naturecoatingsinc.com/>

<sup>7</sup> <https://www.european-coatings.com/news/application-areas/crustacean-chitin-based-coloured-pigments/>

Recently, Archroma (Germany), a global leader in specialty chemicals towards sustainable solutions, introduced the NTR Printing System to make bio-based pigment printing commercially possible for the first time. Archroma's NTR Printing System is the first to utilize renewable feedstock across pigment dispersion, binder and fixing agent, suitable for most popular application technologies, including printing, coating, etc. All the three printing elements are partially based on renewable feedstock to reduce reliance on non-renewable petrochemicals. Two successful bulk trials were conducted with Textprint S.A. and Jeanologia. The NTR printing system comprises: PRINTOFIX® BLACK NTR-TF - a non-gelling black pigment dispersion with 79% renewable carbon content, HELIZARIN® NTR-SS - a formaldehyde-free super-soft binder with 40% renewable carbon content, and LUPRINTOL® FIXING AGENT NTR-HF - a formaldehyde-free fixing agent with 40% renewable carbon content.<sup>8</sup>

Additionally, Kao Collins Inc. has created LUNAJET,<sup>9</sup> the first high-quality water-based pigmented inkjet ink for flexible plastic films, which uses a nanodispersion technology that makes it suitable for non-porous substrates. It is announced as an eco-friendly and safe to use ink. Despite the great achievement in producing a water-based ink for plastics, the formulation, including the pigment, is still fossil base.

Based on the search made, it can be concluded that the market is driven to digital pigment printing inks, but the benchmark is still the synthetic pigment inks. There is still a large gap in the market for reliable bio-based ink formulations for digital printing applications, whichever the value-chain.

## 2.2 Bio-based (polyester based) textiles

The benchmark products for textiles are still quite similar to the ones presented in the proposal, with limited examples of biopolymer textiles available in the market, besides the cellulosic and animal-derived ones.

However, some examples of Polylactic acid (PLA), PHA and others are commercially available. These are listed below.

- **Ingeo™:**<sup>10,11</sup> Ingeo is the trademark brand name for a range of PLA biopolymers owned by NatureWorks (from the USA), the world's largest PLA manufacturer. The feedstock used is the dextrose sugar from plants, mainly corn (their carbon source produced during photosynthesis) - the carbon and other elements in these sugars are used to make biopolymers through a process of fermentation and separation. The resulting resin can be used for different applications, such as injection moulding into plastic goods, extrusion into films, thermoforming into packaging, or extrusion into fibres for textile applications. There are several textile products on the market with this textile fibres, such as pillows, blankets, mattress and apparel;<sup>12</sup>
- **Sorona®:**<sup>13,14</sup> a partially bio-based fibre by DuPont, obtained from the polymerization of bio sourced (sugar from crops) 1,3-Propanediol (PDO) and fossil-based terephthalic acid (TPA). This fibers are applied in different textiles, such as apparel or carpet;
- **Biofeel®:**<sup>15</sup> This is the brand name of the bio-based filaments produced by the RadiciGroup. They have, among others, a bio-PET filament (obtained by the polymerization of 70% purified TPA and 30% Bio-MEG (mono-ethylene glycol) obtained from renewable sources, such as sugar cane and cellulosic waste) and a bio-PLA filament (continuous filament yarn made with PLA resin, from NatureWorks Ingeo®);

<sup>8</sup> <https://www.wtin.com/article/2024/october/14-10-24/breakthrough-in-bio-based-textile-printing/>

<sup>9</sup> <https://www.kaocollins.com/inks/water-based-ink/lunajet/>

<sup>10</sup> <https://www.natureworkslc.com/technology-and-products/ingeo-technology>

<sup>11</sup> [https://www.natureworkslc.com/~media/Technical\\_Resources/Fact\\_Sheets/Fibers/FactSheet\\_Apparel\\_FibertoFabric\\_pdf.pdf](https://www.natureworkslc.com/~media/Technical_Resources/Fact_Sheets/Fibers/FactSheet_Apparel_FibertoFabric_pdf.pdf)

<sup>12</sup> <https://appareltalksbyapurva.wordpress.com/2020/12/10/ingeo-corn-based-fibre/>

<sup>13</sup> [doi.org/10.1007/978-981-10-0522-0\\_5](https://doi.org/10.1007/978-981-10-0522-0_5)

<sup>14</sup> <https://sorona.com/our-story>

<sup>15</sup> <https://www.radicigroup.com/en/products/fibres-and-nw/bio-yarn>

- **Futerro PLA Renew™:**<sup>16</sup> FUTERRO S.A. is a well-established Belgian Company with has extensive industrial experience in lactic acid and PLA production also from plants sugars. Futerro's first industrial plant produces a wide range of bio renewable polymer PLA, RENEW™, for all existing applications (thermoforming, fibres and non-woven, film and coating, injection moulding, blow moulding, 3D printing) with an annual capacity of 100 000 tons making Futerro the second largest PLA producer in the world;
- **PLA t-shirt from Xtep** (Chinese sporting goods brand):<sup>17</sup> In 2020 Xtep<sup>18</sup> launched a new environmentally friendly product, a PLA T-shirt. Similarly to Ingeo™ and Renew™, PLA is mainly extracted from corn, straw and other starch-containing crops and transformed into PLA fibre after spinning. The clothes made of PLA fibre are biodegradable within one year;
- **Mango Materials™:**<sup>19</sup> This innovative company (from the USA) has come up with a way to turn methane from biogas waste into a biodegradable PHA biopolymer, which can then be used to replace the fossil-based fibres in clothing and packaging. MangoMaterials™ produces specifically formulated pellets to meet customer unique material performance requirements being applied in injection moulding, fibres and films;
- **Patagonia SugarDown:**<sup>20</sup> this is a 100% bio-based polyester sourced from US-grown sugarcane. Patagonia established partnerships with a Japan-based textile partner, Toray Industries, which developed a 30% bio-based PET using sugar-based ethylene glycol, and Virent, based in Madison, Wisconsin, that was using innovative technology to turn paraxylene (a sugar-based raw material) into molecules that act like petroleum. The chemical combination of Toray's ethylene glycol and Virent's paraxylene created a petroleum-free version of PET. This bio-based solution had to pass stringent lab and field-testing standards. Responsible sourcing was also paramount, so non-GMO sugarcane grown in Louisiana is used. In 2022, the first SugarDown products, a men's and women's Hoodie with a shell and liner made with the bio-based polyester alternative were presented;
- **TopGreen® Bio PET Filament:**<sup>21</sup> A PET filament made with 30% bio-based feedstock from sugarcane, produced by the Far Eastern's group. This company also produces a bio-based polytrimethylene terephthalate (PTT), and bio-based PLA made with NatureWorks Ingeo™;
- **LYCRA® T400®:**<sup>21</sup> An EcoMade fibre launched in 2018 by INVISTA. Over 65% of the fibre content comes from a combination of chemically recycled plastics (PET bottles) and renewable plant-based resources (corn);
- **Palmetto Synthetics:**<sup>21</sup> offers a bio-based PLA staple fibre made with NatureWorks Ingeo®
- **ECO CIRCLE™ Plantfiber:**<sup>21</sup> a partially bio-based PET resin produced by Teijin, made from 30% bio-based MEG derived from sugarcane 70% petroleum-based dimethyl terephthalate (DMT) or PTA;
- **Ecodear® PET:**<sup>21</sup> a 30% plant-based polyester fibre derived from sugarcane produced by Toray. It also has a 30% plant-based Ecodear® PTT and a 100% bio-based PLA filament;
- **Trevira:**<sup>21</sup> an Indorama Ventures company, offers bio-based PLA fibres and filaments made with Nature Works LLC Ingeo™;
- **Sincdoo's Eco-Friendly PLA Clothing:**<sup>22</sup> Sincdoo is a pioneering biotech company focuses on the development, research, and production of PLA products, including clothing;
- **PHAXTEC™:**<sup>23</sup> it combines hi-tech production and natural material solutions to serve Foodservice Packaging, Agriculture and Personal Care markets, where is included fibres and fabrics;
- **Bluepha® PHA:**<sup>24</sup> family of naturally occurring biopolymers with excellent performance, ensuring a wide range of downstream applications, e.g. rigid and flexible packaging, fibres and fabrics, paper coating, etc.;

<sup>16</sup> <https://www.futerro.com/>

<sup>17</sup> <https://www.businesswire.com/news/home/20210604005128/en/%C2%A0A-Clothing-That-Was-Planted%E2%BC%9A%9A%9A-Xtep-Launched-New-PLA-T-shirts>

<sup>18</sup> <https://en.xtep.com/>

<sup>19</sup> [mangomaterials.com](http://mangomaterials.com)

<sup>20</sup> <https://eu.patagonia.com/pt/en/our-footprint/biobased-polyester.html>

<sup>21</sup> Preferred Fiber & Materials Market Report 2020, Textile Exchange

<sup>22</sup> <https://sincdoo.com/collections/pla-poly-lactic-acid-fibre-clothing>

<sup>23</sup> <https://www.phaxtec.com/>

<sup>24</sup> <https://www.bluepha.bio/>



- **NOOSA®**:<sup>25</sup> 100% bio-based PLA fibre, which is made from corn and sugarcane, 100% recyclable thanks to NOOCYCLE® technology;
- **OceanSafe naNea**:<sup>26</sup> 25-30% bio-based PET staple fibres. Cradle to Cradle Certified® Gold;
- **Kintra Fibers**:<sup>27</sup> compostable bio-synthetic resin and yarns for the apparel industry. Kintra's proprietary materials eliminate petrochemicals and microfiber pollution from the fashion industry by leveraging renewable, toxin-free chemistries and utilizing a cradle-to-cradle mindset during resin development;
- **CELYS™**:<sup>28</sup> first certified compostable polyester fibre distinguished by its unique composition, allowing it to break down efficiently under industrial composting conditions;
- **PlaX™**:<sup>29</sup> novel carbon neutral material with improved quality and function, comprised of PLA developed by Bioworks. Regarding fibre properties, characteristics such as antibacterial properties derived from lactic acid are expected;
- **EVO® by FULGAR**:<sup>30</sup> 100% bio-based yarn based on castor oil and industrial corn, both fully renewable resources that do not require large amounts of water or take away land for food use. It is ultra-light, super stretch and extremely breathable, dries quickly and does not require ironing, being suitable for any textile application.

There still is an extremely limited application of bio-PES, namely PHAs, in the textile sector. PLA fibres are difficult to produce from PLA polymer, exhibit higher sensitivity to alkali causing strength loss, and surface cohesion which gives the fibres a property known as "scoop", which influences resilience and causes problems in applications by resisting recovery after deformation.<sup>31</sup> According to Materials Market Report from Textile Exchange,<sup>32</sup> the market share of bio-based polyester is estimated at around 0.01% of the total polyester production. Mostly, biosynthetic materials that exist on the market are partially bio-based. So, it is extremely important that industry continues to invest in and develop 100% bio-based solutions.

## 2.3 Bio-based (polyester based) shoe soles and insoles

Although there are some bio-based soles and insoles in the market, presented below, and showing a trend for bio-based alternatives in the shoe market, these solutions do not compete directly with the products that **W2BC** is developing, as the solutions available have only a small percentage of bio-based content, and most have a performance not suitable for high-demanding technical applications as the ones developed in the project.

Some solutions of bio-based soles and insoles found in the market include:

- **PLIANT™** with natural rubber soles;<sup>33</sup>
- **Vapesol®** with EVA soles containing some percentage of a bio-based component such as algae or sugar cane (Eva BLOOM® or EVA Green), thermoplastic polyurethane soles derived (only in some percentage) from a corn source, and composites of a mixture of cork waste and thermoplastic rubber (VP NATURAL);<sup>34</sup>
- **VEJA** with outsoles containing 33% rice waste, and insoles containing 51% sugar cane and 21% recycled plastic bottles;<sup>35</sup>
- **Orba™** outsoles obtained using different bio-based additives, as alternatives to the conventional ones: rice husk ash as a "biosilica" instead of using mined silica, coconut oil is used in place of

<sup>25</sup> <https://noosafibre.com/>

<sup>26</sup> <https://www.oceansafe.co/detail/synthetic-fibres>

<sup>27</sup> <https://www.kintrafibres.com/>

<sup>28</sup> <https://www.celys.com.au/>

<sup>29</sup> <https://bioworks.co.jp/en/technology/>

<sup>30</sup> <https://www.fulgar.com/en/products/59/evo-by-fulgar>

<sup>31</sup> [doi.org/10.1007/978-981-10-0522-0\\_5](https://doi.org/10.1007/978-981-10-0522-0_5)

<sup>32</sup> <https://textileexchange.org/app/uploads/2023/11/Materials-Market-Report-2023.pdf>

<sup>33</sup> <https://www.naturalfibrewelding.com/footwear>

<sup>34</sup> <https://vapesol.com/sustainable-soles/>

<sup>35</sup> <https://settingmind.com/veja-launches-its-first-ever-bio-based-running-shoes/>

petroleum-based oils, beeswax instead of petroleum-based paraffin waxes used in synthetic rubbers;<sup>36</sup>

- **Nothing New** with soles made of natural rubber, recycled rubber, and recycled cork;<sup>37</sup>
- **Reebok and VioBarefoot** are integrating Susterra® propanediol, a corn-derived substance characterized by its 100% plant-based composition, into the fabrication of sole and upper sole components;<sup>38</sup>
- **SAOLA outsoles**<sup>39</sup> incorporate Rise, a high-performance foam with 45% renewable content, as a substitute for conventional petroleum-derived EVA. Rise is formulated utilizing a composite blend of resin, algae biomass (comprising 20% algae content), and bio-sourced additives;<sup>40</sup>
- **Rothy's** shoes with eco-friendly rubber outsoles that contain 26% natural minerals-sand. The outsoles of their signature loafers are made with 9% natural, renewable rubber from rubber plants.<sup>41</sup> Rothys also use castor oil derived from castor beans in the development of insoles, crafted with a bio-based polyurethane that utilizes castor oil as a more environmentally friendly plant source;
- **Allbirds** has launched a range of flip-flops called Sugar Zeppers. The material of the soles is a sugarcane bioplastic produced by Braskem trademarked SWEETFOAM™ and referred to as bio-EVA;<sup>42</sup>
- **BioCir® Flex**, developed by **Balena**, is a DIN-certified thermoplastic elastomer that is 50-85% bio-based, durable, flexible, and fully compostable. It is designed for a clear circular end-of-life, recyclable, and suitable for producing durable consumer goods via injection moulding, extrusion, and 3D printing with filaments or pellets. Notably, it has been used for outer soles;<sup>43</sup>
- **Sneature**, designed by Emilie Burfeind, is a customizable, waste-based sneaker with a 3D-printed mycelium sole. It is fully biodegradable and can be returned to the natural material cycle as nutrients after use;<sup>44</sup>
- **BLUEVIEW** shoes use **Soleic™ Foam** in the development of insole and outsole that fully biodegrades into its component chemicals in soil and compost. This claim is supported by peer-reviewed papers;<sup>45</sup>
- **Orba™** three layered insoles containing cork in the top layer, coconut husk in the two lower layers, and agave sisal in the lower layer;<sup>36</sup>
- **Eco-Ortholite™** insoles by Eco Vegan Shoes, made using a formula that replaces 20% of the petroleum traditionally used by a PU made from castor beans;<sup>46</sup>
- **Foam Well** with insoles containing 25% bio-based (seaweed) and recycled foam;<sup>47</sup>
- **OrthoLite® Hybrid™** uses a patent-pending formulation that uniquely combines 5% recycled rubber and 15% production waste foam, achieving an impressive 20% eco-content (not bio-content);<sup>48</sup>
- **Tunera™** is announced as a bio-neutral, plastic-free foam perfect for footwear insoles, but its composition has not been revealed. The product has not been launched yet;<sup>49</sup>
- **Guppyfriend® Organic Insoles** claims to be biodegradable and uses 100% natural materials, including natural cotton, latex, kenaf, corn, and linen;<sup>50</sup>
- **Fulton™** sustainable shoe insoles are made of three layers: carbon negative cork, latex foam, and a cactus leather liner;<sup>51</sup>

<sup>36</sup> <https://orbashoes.eco/pages/materials>

<sup>37</sup> <https://nothingnew.com/pages/materials>

<sup>38</sup> <https://www.bioplasticsmagazine.com/en/news/meldungen/20220128-Huntsman-develops-bio-based-polyurethane-for-Keen-s-plant-based-soles.php>

<sup>39</sup> <https://eu.saolashoes.com/pages/eco-conception>

<sup>40</sup> <https://www.bloommaterials.com/rise/>

<sup>41</sup> <https://rothys.com/en-pt/pages/materials>

<sup>42</sup> <https://www.biopreferred.gov/BioPreferred/faces/pages/articles/Shoes.xhtml>

<sup>43</sup> <https://balena.science/pages/biocirflex-1>

<sup>44</sup> <https://distributeddesign.eu/awards/entries/sneature-waste-based-footwear/>

<sup>45</sup> <https://blueviewfootwear.com/pages/eco-friendly-materials>

<sup>46</sup> <https://www.eco-vegan-shoes.com/accessories/insoles>

<sup>47</sup> <https://www.insolefoam.com/new-bio-based-with-seaweed-added-insole.html>

<sup>48</sup> <https://www.ortholite.com/sustainability/>

<sup>49</sup> <https://www.naturalfibrewelding.com/footwear>

<sup>50</sup> <https://en.guppyfriend.com/products/guppyfriend-organic-insoles?variant=44272623452425>

<sup>51</sup> <https://walkfulton.com/>

- **Tread & Butter™** carries out four types of insoles, all made using the same sustainable cork;<sup>52</sup>
- **Hemp Organic Insoles** are all natural, with an all-hemp inner wrapped in an organic Hemp and Cotton outer;<sup>53</sup>
- **KO-SI®** insoles are made from natural, renewable and completely biodegradable materials. The non-woven textile base made of coir or sisal fibres can be coated with a layer of sheep wool or lyocell for additional softness and thermal insulation. No synthetic binders and adhesives are used; instead, only 100% natural latex is used;<sup>54</sup>
- **7-gram startup** have developed eco-friendly coffee insoles from up-cycling coffee cups and bagasse;<sup>55</sup>
- **STANLEY PARK Organic Hemp Insole Footbed** by Rawganique has been declared the world's first truly natural and 100% biodegradable insole. This innovative product features three heat-pressed layers: organic hemp on the top, natural rubber padding in the middle, and felted hemp on the bottom. Completely free from plastic, polyvinyl chloride, vinyl, polyester, and toxic chemicals;<sup>56</sup>
- **Elevated Clouds®** from Primal Soles sustainable cork insoles are the world's first carbon-negative and circular insoles, made from regenerative Mediterranean cork and upcycled shoe waste. Expertly crafted for maximum comfort, they feature natural, recyclable cork with a unique honeycomb structure and Suberin components, making them antibacterial, lightweight, shock-absorbing, moisture-wicking, and thermally regulating;<sup>57</sup>
- **Patin-A** offers a range of 100% natural, vegan, and sustainable insoles, including the Footsanit Flat Coconut Sole and the Footsanit Sisal Sole;<sup>58</sup>
- **ECO Plantar Fasciitis** by Green Steps is certified with up to 76% renewable bio-content.<sup>59</sup>

It was possible to observe that, although some bio-based alternatives for soles and insoles are available in the market these are still limited and are mostly based on the mix of natural components (sometimes coming from wastes) with synthetic binders, which can impact either their recyclability or their biodegradability.

## 2.4 Bio-based (polyester based) plastic packaging

Environmental issues are becoming increasingly important to the European consumer. Consequently, consumer pressure is triggering the use of bio-based packaging materials as an alternative to materials produced from non-renewable resources.<sup>60</sup> There are several bio-polyester based packaging products in the market. However, there is still a huge demand on the biodegradable packaging materials for the reduction of micro-plastics pollution, and recyclability, for increased sustainability credentials, preferably through the same recycling routes as fossil-based polyester.

Some biodegradable biopolymer solutions for food packaging applications like films, foams and composites made of e.g., cellulose (i.e., cellophanes), zein, PLAs and scl-PHAs are already commercialized (e.g., Cozeen 303N26 based on zein, PHB Biopol® from Metabolix with properties similar to PP produced through fermentation). However they present several limitations, such as high brittleness, low flexibility, low transparency and yellowish to greenish appearance of Biomax® foils, high environmental impact of manufacture stages for some natural polymers like soy proteins or high-energy consuming production of films, e.g., chitosan and agar films.<sup>61</sup> Additionally, it is difficult to process the non-thermoplastic character of cellulose which requires hazardous viscose processing

<sup>52</sup> <https://www.thegoodtrade.com/features/shoe-inserts-insoles/>

<sup>53</sup> <https://www.thehempshop.co.uk/hemp-organic-insoles.html>

<sup>54</sup> <https://www.ko-si.si/en/Products/Insoles>

<sup>55</sup> <https://www.trendhunter.com/trends/coffee-insoles>

<sup>56</sup> <https://rawganique.com/collections/organic-insoles/products/organic-hemp-insole-footbed-regular?currency=USD>

<sup>57</sup> <https://primalsoles.com/products/primal-elevated-clouds-cork-insoles>

<sup>58</sup> <https://www.patin-a.de/en/leather-shoe/insoles/organic-vegan-recycled-sustainable>

<sup>59</sup> <https://footactive.co.uk/arch-support-insoles/green-steps-eco-plantar-fasciitis-sustainable-insoles>

<sup>60</sup> [doi.org/10.1016/S0924-2244\(99\)00019-9](https://doi.org/10.1016/S0924-2244(99)00019-9)

<sup>61</sup> [doi.org/10.1016/j.jclepro.2013.07.054](https://doi.org/10.1016/j.jclepro.2013.07.054)

for production of cellophanes, leading to a higher cost of 100% bio-based PET compared to conventional one. Although the higher price, the deformability, tensile and impact strength is lower for the common PHB-based packaging materials compared to petroleum-based ones. PHB Biopol® is more expensive than fossil based, has a longer fermentation process, low resistance to acids and bases. For food packaging, DaklaPack® has a solution of a fully compostable bag, made entirely from PLA obtained from corn and sugar cane.<sup>62</sup> Bio-Flex® is a product family of technically advanced and innovative biopolymers that combine renewability, biodegradability and compostability. The natural raw material basis of these PLA blends is corn, sugar cane or castor oil. When compared to starch-based bioplastics, Bio-Flex® is more resistant to mechanical stress and moisture which makes it suitable for applying in the packaging of food, clothing and make-up.<sup>63</sup>

Some other examples of bio-based PET plastics available in the market include:

- **PlantBottle™** produced by the Coca-Cola company,<sup>64</sup> a 100% recyclable PET with up to 30% bio-based content;
- **Ecovio®**<sup>65</sup> from BASF, a compostable and partially bio-based polymer. "It consists of the compostable BASF polymer ecoflex®, PLA and other additives";
- **Green™ Polyethylene**<sup>66</sup> a bio-based PE for extrusion, injection moulding, and blow moulding, produced from sugar cane. It is a 100% recyclable plastic;
- **NatureFlex™**: a range of speciality packaging films obtained from renewable resources (wood-pulp from managed plantations) developed by Futamura.<sup>67</sup> They provide barrier and heat resistance and are often used for flexible packaging applications, including films, bags, and labels;
- **EcoCortec** also produces biodegradable and compostable films and bags, named VpCI®, based on a variety of biopolymers which can be used in packaging;<sup>68</sup>
- **Tipa®** provides compostable packaging solutions made from bio-based (up to 66%) and fossil-based materials. Their products are made from a formula of blend or fully compostable polymers, which give them the properties and functionality of conventional plastics such as PE and PP;<sup>69</sup>
- **Luminy®**<sup>70</sup> are PLA biopolymers produced by TotalEnergies Corbion, a global technology leader in PLA and lactide monomers. The PLA is a bio-based, recyclable, and biodegradable polymer made from annually renewable resources, namely sugarcane.
- **Eastman TREVA™**<sup>71</sup> is a cellulose-based bioplastic with a bio-based content of 45%. It offers a high performance and a reduced environmental impact. Also, it is chemically resistant, dimensionally stable and has excellent flow, BPA-free and low birefringence.
- **Avantium PEF™**<sup>72</sup> is a bio-based alternative to PET called polyethylene furanoate (PEF). It is produced from plant-based feedstocks such as sugar and offers enhanced barrier properties compared to PET, making it suitable for packaging applications. Avantium has been collaborating with partners to scale up production and bring PEF-based products to market;

<sup>62</sup> <https://www.daklapack.eu/bio-based/gripbags/gripbag-compostable-60-mm-x-80-mm-semi-transparent/8712963031374>

<sup>63</sup> <https://fkur.com/en/bioplastics/bio-flex/>

<sup>64</sup> <https://www.coca-colacompany.com/about-us/faq/what-is-plantbottle-packaging>

<sup>65</sup> [https://plastics-rubber.basf.com/global/en/performance\\_polymers/products/ecovio.html?at\\_medium=sl&at\\_campaign=PM\\_BAW\\_GLOB\\_EN\\_ecovio\\_TRA\\_CROSS&at\\_term=ecovio&at\\_creation=Search\\_Google\\_SERP\\_ecovio-General-Global-EN&at\\_platform=google&at\\_variant=ecovio-General-Global-EN&gclid=CjwKCAjw67ajBhAVEiAw2g\\_jEMoxOEZ1AoSBFCAAhhMqYTWgJvrvVpWHcV8KJAa4mErvO mjGwFF0TxoCNKAQAvD\\_BwE](https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html?at_medium=sl&at_campaign=PM_BAW_GLOB_EN_ecovio_TRA_CROSS&at_term=ecovio&at_creation=Search_Google_SERP_ecovio-General-Global-EN&at_platform=google&at_variant=ecovio-General-Global-EN&gclid=CjwKCAjw67ajBhAVEiAw2g_jEMoxOEZ1AoSBFCAAhhMqYTWgJvrvVpWHcV8KJAa4mErvO mjGwFF0TxoCNKAQAvD_BwE)

<sup>66</sup> <https://fkur.com/en/bioplastics/im-green-polyethylene/>

<sup>67</sup> <https://www.futamuragroup.com/en/divisions/cellulose-films/products/natureflex/>

<sup>68</sup> <https://ecocortec.hr/eng/index>

<sup>69</sup> [https://tipa-corp.com/bio\\_plastic\\_technology/](https://tipa-corp.com/bio_plastic_technology/)

<sup>70</sup> <https://www.totalenergies-corbion.com/>

<sup>71</sup> <https://www.eastman.com/en/products/product-detail/71110438/treva-engineering-bioplastic-gc6011-clear>

<sup>72</sup> <https://avantium.com/>

- **Ingeo™** is a unique bio-based material, using plant sugars from field corn as the source material instead of oil. It is produced on a commercially viable scale by NatureWorks LLC and performs well in both its plastic and fibre forms.<sup>73</sup>

From the search made, it is possible to realize that despite the presence of different bio-based PET<sup>74</sup> in the market made from renewable sources, many come from sugarcane or plant-based biomass, which can compete with the food industry / agricultural areas, indicating the demand for alternative sources to produce the bio-based plastics.

## 2.5 Chemical recycling (depolymerization and re-polymerization) of polyester materials

### 2.5.1 Polyester textiles and plastics chemical recycling

Currently, most of the recycling technologies for polyester are focused on thermal/mechanical downcycling of i) polyester fibre into other applications, such as, fillings for the automotive industry or home textiles,<sup>75</sup> and ii) plastics into similar products but to the expense of virgin material to be able to produce products with similar properties.

Depending on the target polymer, chemical recycling companies use various technologies of chemical recycling. In general, three different chemical recycling approaches are applied for polyester and polyester/cotton blends: (1) solvent-based dissolution, (2) hydrothermal, and (3) enzymatic/biochemical. Below are some examples of these.

*Table 1. Examples of chemicals recycling technologies in the market for polyester textiles and plastics*

Company	Technology	Input material	Output	Capacity	Notes
<b>Circulose®</b> <sup>76</sup>	re:newcell Chemical recycling based on dissolution	Colourless Pre- and post-consumer waste CO and PES/CO with high cellulose content	Pulp dried into sheets	Production capacity 60 000 metric tonnes/yr	The recycling is of the cellulose content, not the PES
<b>Södra</b> <sup>77</sup>	Chemical recycling based on dissolution	Pre- and post-consumer waste, CO and PES/CO with high cellulosic content	Cellulosic pulp with 50% recycled content	Production scale 2 000 metric tonnes/yr	The recycling is of the cellulose content, not the PES
<b>Plast Nordic</b> <sup>78</sup>	GR3N technology: depolymerisation/ Alkaline hydrolysis plus microwave technology	PET-based waste like PES, PES/CO, plastic bottles, food containers	Recycled monomers (PTA and MEG), building blocks for synthetic polymers	30 000 metric tonnes/yr/plant	Chemical recycling of PES / PET

<sup>73</sup> [https://www.natureworkslc.com/~media/news\\_and\\_events/natureworks\\_theingeojourney\\_pdf](https://www.natureworkslc.com/~media/news_and_events/natureworks_theingeojourney_pdf)

<sup>74</sup> <https://biokunststofftool.de/materials/bio-pet/?lang=en>

<sup>75</sup> Fibersort. Recycled post-consumer textiles an industry perspective. 2020

<sup>76</sup> <https://www.renewcell.com/en/>

<sup>77</sup> <https://www.sodra.com/>

<sup>78</sup> <https://www.gr3n-recycling.com/>

Company	Technology	Input material	Output	Capacity	Notes
<b>TextileChange</b> <sup>79</sup>	Chemical recycling based on depolymerising into monomers	Pre- and post-consumer waste PES and PES/CO	Cellulose pulp and PES pellets for extrusion/spinning of fibres	Lab scale	Chemical recycling of both cellulose and PES / PET, but not clear
<b>CuRe Polyester Rejuvenation</b> <sup>80</sup>	Chemical recycling based on depolymerisation into polymers	Industrial, pre- and post-consumer PES waste	rPET pellets	Pilot scale 320 kg/h, planning 25 000 metric tonnes/yr and the technology licensed	Chemical recycling of PES not clear
<b>CLS-Tex</b> <sup>81</sup>	HTEX mechanical and chemical recycling into building blocks	Post-consumer work wear and uniforms made of PES (and PES / CO)	Monomer building blocks for new PES fibres	Not known	Chemical recycling of PES
<b>Worn Again technologies</b> <sup>82</sup>	Chemical recycling into "clean" polymers	Post-consumer textile waste PES/CO, PET bottles, plastic waste	PET resin and cellulosic pulp	1 000 metric tonnes/yr textile waste	Chemical treatment to separate PES from cellulose and remove contaminants , to allow production of new fibres or plastics
<b>Pure Loop</b> <sup>83</sup>	Chemical and thermal recycling	Post-consumer textile waste or plastics	PET flakes or pellets	Not known	Not clear if chemical recycling or just thermal
<b>Teijin Frontier Co</b> <sup>84,85</sup>	Chemical recycling into monomers	PES fibres	Purified BHET intermediate raw material that is repolymerized into PES	Not known	Chemical recycling of PES and PET
<b>Loop Industries</b> <sup>86</sup>	Chemical recycling into monomers (methanolysis)	PET plastic and PES fibre waste	Monomers, DMT and MEG, which are then polymerized into new PET /PES	Not known	Chemical recycling of PES and PET

<sup>79</sup> <https://textilechange.com/>

<sup>80</sup> <https://curetechnology.com/>

<sup>81</sup> <https://www.cls-tex.com/>

<sup>82</sup> <https://wornagain.co.uk/>

<sup>83</sup> <https://www.pureloop.com/en/pet-fibres/>

<sup>84</sup> <https://www.just-style.com/news/teijin-frontier-launches-chemical-recycling-tech-for-polyester-fibres/>

<sup>85</sup> <https://www2.teijin-frontier.com/english/news/post/120/>

<sup>86</sup> <https://www.loopindustries.com/en/technology>



Company	Technology	Input material	Output	Capacity	Notes
<b>Eastman<sup>87</sup></b>	Chemical recycling (glycolysis or methanolysis) into monomers	PES	Monomers	Not known	Chemical recycling of PES and PET
<b>Unifi<sup>88</sup> / REPREVE<sup>89</sup></b>	Chemical recycling	PET bottles and post-industrial and post-consumer waste	Recycled PET fibres	In 2023 Unifi recycled the equivalent to 750 millions of t-shirts.	
<b>Syre<sup>90</sup></b>	Chemical recycling by depolymerization	Post consumer textile waste	BHET that is polymerized to PET	Industrial scale	Chemical recycling of PES
<b>NextChem<sup>91</sup></b>	Depolymerization by alkaline hydrolysis and microwaves	PET and polyester from textiles	Pure monomers to produce new polymers	Demonstration plant	Part of the European Union's DEMETO project

In more detail, some examples of technologies are next highlighted:

- The CuRe technology is a low energy recycling of PES to polymer level (without decomposing the polyester to monomer). Depending on the type of PES of the input material, the best route can be chosen since it's a modular and flexible technology. Any type of pure PES can be recycled, and the dye/colour be removed. The output are PET pellets that can, supposedly, be polymerised with the same properties as virgin polyester;
- Worn Again technology separates PES / CO fabrics by dissolution in a close loop system, followed by polymer separation and restoring (for PET) and cellulosic polymers. The resulting products of the process are PET-resin for spinning of new PES-fibres and cellulosic pulp for spinning of viscose/lyocell fibres, that further can be applied to spin yarn and weave/knit fabric for garments. This technology allows to process 80% of post-consumer waste;
- Teijin Frontier Co has developed a recycling technology of PES fibres using a "depolymerisation catalyst for the conventional bis (2-hydroxyethyl) terephthalate (BHET) method, spent PES is chemically decomposed and purified back into BHET intermediate raw material before being repolymerized into polyester". They also recycle plastic packaging;
- Loop Industries has developed a depolymerization process called "Infinite Loop" that breaks down previously unrecyclable PET plastic and PES fibre waste into their monomers, dimethyl terephthalate and monoethylene glycol. These monomers are purified and polymerized (or recombined) into Loop™ branded PET plastic and polyester fibre, 100% recycled;
- Eastman developed a depolymerization technology called "Polyester Renewal Technology", that is based on either glycolysis or methanolysis. The resulting monomers are indistinguishable from materials made with virgin or nonrecycled content.
- Revalyu explores the depolymerization of used plastic PET bottles (i.e., multi-ester molecules) into sustainable esters (monomers). These monomers can be used to manufacture all PET based products such as polyester textiles, PET bottles, film, sustainable PET packaging, etc. The glycolysis process occurs at a low temperature and as chemical solvent use MEG; <sup>92</sup>

<sup>87</sup> <https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Polyester-Renewal.aspx>

<sup>88</sup> <https://unifi.com/sustainability/approach>

<sup>89</sup> <https://repreve.com/>

<sup>90</sup> <https://www.syre.com/>

<sup>91</sup> <https://www.groupmaire.com/en/newsroom/news/first-demonstration-plant-for-chemical-recycling-textiles/>

<sup>92</sup> <https://www.revalyu.com/>

- Ioniqa depolymerizes (glycolysis) of all types and colours of PET waste into valuable resources for 'virgin- quality' new PET;<sup>93</sup>
- Axens technology works with any type of plastic waste following depolymerization by glycolysis and a purification step to obtain a purified monomer (recycled BHET) and also the recovery and valorisation of pigments and dyes;<sup>94</sup>
- Protein Evolution presented Biopure™ technology that uses AI-designed enzymes for plastic waste recycling. The resulting material is used to create 100% recycled plastic by packaging companies and fashion brands;<sup>95</sup>
- Samsara eco applies enzymes to recycle PET and polyester (polymers) into the original components (monomers). The recycled monomers can be used in re-manufacturing new plastics, including food-grade packaging;<sup>96</sup>
- Carbios technology of enzymatic recycling (depolymerization by hydrolysis-using water as reagent) of all types of PET, including those present in plastics or textiles. According to the company, it is possible to recover PET waste that cannot be recovered by the conventional recycling technologies. This research included the identification and optimization of wild type enzymes to improve their polymer degradation activity and thermostability.<sup>97</sup> One of the enzymes developed is a PET hydrolase capable of achieving a minimum of 90% PET depolymerization into monomers within 10 hours and exhibits a high productivity, yielding 16.7 grams of terephthalate per litre per hour.<sup>98</sup>

As evidenced by the search results, the chemical recycling, by depolymerization and re-polymerisation, of PES / PET polymers is still in its first stages. Most processes in the market that claim to make chemical recycling, are in fact thermal recycling (melting and extrusion into pellets), which typically do not allow a "closed-loop" recycling, as to obtain material with the same properties, virgin pellets need to be added to the mixture.<sup>99</sup> Also, no information was found for the recycling of bio-based PES, although the producers of these often claim that they are fully recyclable.

## 2.5.2 Footwear (soles and insoles) chemical recycling

The worldwide footwear production reached 24 billion pairs per year, from which only 5% are recycled or reused.<sup>100</sup> The footwear difficulty to recycle is related to the complexity of the materials which are used in footwear production, including leather, textiles, rubber, foam, plastics, and metals. Each material may require a different recycling process, making it challenging to efficiently separate and recycle them.

Similarly to textile waste, in the case of footwear most of the recycling process are performed by mechanical process. The LIFE-ECOTEX project (2019) demonstrated the feasibility of a closed-loop recycling of waste PES textiles from footwear into new textile products using glycolysis technology. The BHET monomers from the PES waste were re-polymerised to obtain chemically recycled PET with a similar quality to virgin PET. The recycled PET was then used to produce PES staple fibres that could be used in the manufacture of non-woven felts to further produce shoe insoles or insulation panels.<sup>101</sup>

<sup>93</sup> <https://ioniqa.com/>

<sup>94</sup> <https://www.axens.net/markets/plastic-recycling>

<sup>95</sup> <https://www.protein-evolution.com/technology>

<sup>96</sup> <https://www.samsaraeco.com/our-technology>

<sup>97</sup> <https://www.carbios.com/en/enzymatic-recycling/>

<sup>98</sup> [doi.org/10.1038/s41586-020-2149-4](https://doi.org/10.1038/s41586-020-2149-4)

<sup>99</sup> [doi.org/10.3390/waste1040050](https://doi.org/10.3390/waste1040050)

<sup>100</sup> WorldFootwear 2019 YearBook

<sup>101</sup> <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE15-ENV-ES-000658/demonstration-of-polyester-of-footwear-waste-recycling-into-new-textile-products-using-glycolysis-technology>



The Footwear Technology Center of La Rioja has carried out a R&D project, together with other entities, where they were able to chemically recycle PU soles into the original compounds, which could be foamed again into recycled PU.<sup>102</sup>

Vivobarefoot established a partnership with a textile recycling company, B Corp Circ, to design and develop footwear uppers made entirely of a single material (PES) that can be chemically recycled and reused in the production of new footwear without the need to add any virgin materials.<sup>103</sup>

Despite these initiatives, the recycling of footwear, namely of soles and insoles, is still largely based in shredding and grinding the materials for reuse.<sup>103,104</sup> But shredded materials often require the addition of virgin plastics to maintain their integrity, resulting in material mixtures that cannot be recycled again.

Specifically in relation to foams, the most common used in soles and insoles are PU or EVA-based. We still have not found information on implemented methodologies for the chemical recycling of these materials. There are some brands that divulge the use of recycled sole materials, but no specifics on how the recycling is made are provided:

- **Vapesol:**<sup>105</sup> this company produces EVA recycled soles, some with a mixture of recycled EVA from the reversions of the expansion process that occurs during injection;
- **Komrads:**<sup>106</sup> produce recycled rubber soles from recycled rubber from tires.

<sup>102</sup> <https://www.ctcr.es/en/proyectos-3/2357-recalza-suelas-2>

<sup>103</sup> <https://www.vivobarefoot.com/us/blog/circ-partnership-launch>

<sup>104</sup> US20110183559A1, Method for Recycling Waste Shoe Soles and a Laminate Made According to the Method

<sup>105</sup> <https://vapesol.com/sustainable-recycled-soles/>

<sup>106</sup> <https://komrads.world/blogs/news/recycled-rubber-the-sole-of-our-products>



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