Report on benchmarking and technology watch

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List of Abbreviations

Acronyms	Description
BHET	Bis(2-hydroxyethyl) terephthalate
CO	Cotton
DMT	Dimethyl terephthalate
EVA	Ethylene-vinyl acetate
M	Month
MEG	Mono-ethylene glycol
PDO	1,3-Propanediol
PE	Polyethylene
PES	Polyester
PET	Polyethylene terephthalate
PLA	Polylactic acid
PHA	Poly-hydroxyalkanoate
PHB	Polyhydroxybutyrate
PP	Polypropylene
PTT	Polytrimethylene terephthalate
PU	Polyurethane
scl-PHA	Short chain length PHA
T	Task
TPA	Terephthalic acid
WP	Work package
yr	Year

1. Introduction

This report represents the first version of the Deliverable 7.4 Report on benchmarking and technology watch, which will be updated on M30. It describes **waste2biocomp** 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 **waste2biocomp** by raising awareness about the project's results and making them available to the multiple stakeholders;
- providing the tools and develop 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 **waste2biocomp** 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 is being performed, to analyse all the possible limitations and weakness of the innovative products under development. Thus, a Benchmarking study was performed in **waste2biocomp** 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 and thermoforming will be compared with commercial fossil-based ones, namely PES and PE based ones from partner PROPAGROUP;
- The textile non-woven coatings for technical textiles obtained by electrospray 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. Further along the project, this benchmarking will be optimized, and different indicators will be defined to allow the identification of detailed differences in procedure and performance.

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). The 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, no inks for inkjet printing with bio-based pigments or dyes have been 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, was found out one textile digital printing company, Torrecid, who launched 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. Based on this exhibition it can be concluded that the market is driven to digital textile pigment printing inks, but the benchmark is still the synthetic pigment inks.

Other alternative bio-based pigments, with the potential to be used in the production of digital printing bio inks, found on the market include:

- Red fungal fermentation pigment from CHROMOLOGICS.[1] Sustainly.Red® has already been tested in textile applications, namely digital and traditional printing, looking for natural and sustainable red colour to substitute artificial dyes;
- Microbial and enzymatic indigo pigment from Huue,[2] who creates microbes that mirror nature's process and consume sugar to enzymatically produce dye;
- Bacterial dyes from Vienna Textile Lab.[3] Natural textiles (originating from plants and animals), as well as synthetic textile fibres, have been successfully dyed with these dyes, but they are still not commercially available;
- Bacterial pigment extract from Faber Futures.[4] 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;[5]
- 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.[6]

Additionally, Kao Collins Inc. has created LUNAJET,[7] 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.

[1] https://www.chromologics.com/
[2] https://www.huue.bio/
[3] https://www.viennatextilelab.at/
[4] https://faberfutures.com/
[5] https://www.graviky.com/
[6] https://www.naturecoatingsinc.com/
[7] https://www.kaocollins.com/inks/water-based-ink/lunajet/

It can be concluded that there is still a large gap in the market for reliable bio-based ink formulations for digital printing applications, in particular for textiles, leather, paper and plastics.

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), Poly-hydroxyalkanoate (PHA) and others are commercially available. These are listed below.

- **Ingeo™:**[8,9] 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;[10]
- **Sorona®:**[11,12] 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®:**[13] 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®);
- **Futerro PLA Renew™:**[14] 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):[15] In 2020 Xtep[16] 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™:**[17] 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;

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[8] https://www.natureworksllc.com/technology-and-products/ingeo-technology

[9] https://www.natureworksllc.com/~/media/Technical_Resources/Fact_Sheets/Fibers/FactSheet_Apparel_FibertoFabric_pdf.pdf

[10] https://appareltalksbyapurva.wordpress.com/2020/12/10/ingeo-corn-based-fiber/

[11] doi.org/10.1007/978-981-10-0522-0_5

[12] https://sorona.com/our-story

[13] https://www.radicigroup.com/en/products/fibres-and-nw/bio-yarn

[14] https://www.futerro.com/

[15] https://www.businesswire.com/news/home/20210604005128/en/%C2%A0A-Clothing-That-Was-Planted%EF%BC%9AXtep-Launched-New-PLA-T-shirts

[16] https://en.xtep.com/

[17] mangomaterials.com

- **Patagonia SugarDown:**[18] 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 Hoody with a shell and liner made with the bio-based polyester alternative were presented;
- **TopGreen® Bio PET Filament:**[19] 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®:**[19] 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:**[19] offers a bio-based PLA staple fibre made with NatureWorks Ingeo®
- **ECO CIRCLE™ Plantfiber:**[19] 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:**[19] 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:**[19] an Indorama Ventures company, offers bio-based PLA fibres and filaments made with Nature Works LLC Ingeo™.

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 "scroop", which influences resilience and causes problems in applications by resisting recovery after deformation.[20]

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 **waste2biocomp** 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;[21]
- **Vapesol©** with EVA soles containing some percentage of a bio-based component such as algae or sugar cane (Eva BLOOM® or EVA Green), TPU soles derived (only in some percentage) from a corn source, and composites of a mixture of cork waste and thermoplastic rubber (VP NATURAL);[22]
- **VEJA** with outersoles containing 33% rice waste, and insoles containing 51% sugar cane and 21% recyled plastic bottles;[23]
- **Orba™** outer soles 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 petroleum-based oils, beeswax instead of petroleum-based paraffin waxes used in synthetic rubbers;[24]

[18] https://eu.patagonia.com/pt/en/our-footprint/biobased-polyester.html
[19] Preferred Fiber & Materials Market Report 2020, Textile Exchange
[20] doi.org/10.1007/978-981-10-0522-0_5
[21] https://www.naturalfiberwelding.com/footwear
[22] https://vapesol.com/sustainable-soles/
[23] https://settingmind.com/veja-launches-its-first-ever-bio-based-running-shoes/
[24] https://orbashoes.eco/pages/materials

- **Nothing New** with soles made of natural rubber, recycled rubber, and recycled cork;[25]
- **Orba™** three layered insoles containing cork in the top layer, coconut husk in the two lower layers, and agave sisal in the lower layer;[24]
- **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;[26]
- **Foam Well** with insoles containing 25% bio-based (seaweed) and recycled foam;[27]
- **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;[28]
- **SAOLA outersoles**[29] 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;[30]
- **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.[31] Rothy's 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 Zeffers. The material of the soles is a sugarcane bioplastic produced by Braskem trademarked SWEETFOAM™ and referred to as bio-EVA;[32]
- **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);[33]
- **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.[34]

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.[35] 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.

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 greenly 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;[36] difficult-to-process non-thermoplastic character of cellulose requiring hazardous viscose processing for production of cellophanes, higher cost of 100 % bio-based PET compared to conventional one, obviously higher price and lower deformability, tensile and impact strength of common PHB-based packaging

[25] https://nothingnew.com/pages/materials
[26] https://www.eco-vegan-shoes.com/accessories/insoles
[27] https://www.insolefoam.com/new-bio-based-with-seaweed-added-insole.html
[28] https://tinyurl.com/2d3azzbc
[29] https://eu.saolashoes.com/pages/eco-conception
[30] https://www.bloommaterials.com/rise/
[31] https://rothys.com/en-pt/pages/materials
[32] https://tinyurl.com/3aypra7m
[33] https://www.ortholite.com/sustainability/
[34] https://www.naturalfiberwelding.com/footwear
[35] doi.org/10.1016/S0924-2244(99)00019-9
[36] doi.org/10.1016/j.jclepro.2013.07.054

materials compared to petroleum based ones, PHB Biopol® more expensive than fossil based, longer fermentation process, low resistance to acids and bases.

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

- **PlantBottle™** produced by the Coca-Cola company,[37] a 100% recyclable PET with up to 30% bio-based content;
- **Ecovio®**[38] from BASF, a compostable and partially bio-based polymer. "It consists of the compostable BASF polymer ecoflex®, polylactid acid (PLA) and other additives";
- **Green™ Polyethylene**,[39] 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.[40] 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;[41]
- **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;[42]
- **Luminy®**[43] 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.

From the search made, it is possible to realize that despite the presence of different bio-based PET[44] is the market made from renewable sources, many come from sugarcane or plant-based biomass, which can compete with the food industry, indicating the demand for alternative sources for the production of 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,[45] 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

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[37] https://www.coca-colacompany.com/about-us/faq/what-is-plantbottle-packaging
[38] 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=CjwKCAjw67ajBhAVEiwA2g_jEMoxOEZ1AoSBFCAAhhMqYTWgJvrvVpWHcV8KJAa4mErvOmjGwFF0TxoCNKAQAvD_BwE
[39] https://fkur.com/en/bioplastics/im-green-polyethylene/
[40] https://www.futamuragroup.com/en/divisions/cellulose-films/products/natureflex/
[41] https://ecocortec.hr/eng/index
[42] https://tipa-corp.com/bio_plastic_technology/
[43] https://www.totalenergies-corbion.com/
[44] https://biokunststofftool.de/materials/bio-pet/?lang=en
[45] Fibersort. Recycled post-consumer textiles an industry perspective. 2020

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
Circulose® [46]	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
Södra[47]	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
Plast Nordic[48]	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
TextileChange[49]	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
CuRe Polyester Rejuvenation[50]	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
CLS-Tex[51]	HTEX mechanical and chemical	Post-consumer work wear and uniforms made of	Monomer building blocks for	Not known	Chemical recycling of PES

[46] https://www.renewcell.com/en/
[47] https://www.sodra.com/
[48] https://www.gr3n-recycling.com/
[49] https://textilechange.com/
[50] https://curetechnology.com/
[51] https://www.cls-tex.com/

Company	Technology	Input material	Output	Capacity	Notes
	recycling into building blocks	PES (and PES / CO)	new PES fibres		
Worn Again tecnologies[52]	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
Pure Loop[53]	Chemical and thermal recycling	Post-consumer textile waste or plastics	PET flakes or pellets	Not known	Not clear if chemical recycling or just thermal
Teijin Frontier Co[54,55]	Chemical recycling into monomers	PES fibres	Purified BHET intermediate raw material that is repolymerized into PES	Not known	Chemical recycling of PES and PET
Loop Industries[56]	Chemical recycling into monomers	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
Eastman[57]	Chemical recycling (glycolysis or methanolysis) into monomers	PES	Monomers	Not known	Chemical recycling of PES and PET

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,

[52] https://wornagain.co.uk/
[53] https://www.pureloop.com/en/pet-fibers/
[54] https://www.just-style.com/news/teijin-frontier-launches-chemical-recycling-tech-for-polyester-fibres/
[55] https://www2.teijin-frontier.com/english/news/post/120/
[56] https://www.loopindustries.com/en/technology
[57] https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Polyester-Renewal.aspx

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 re-combined) 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.

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.[58] 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.[59] 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 the majority 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.[60]

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.[61]

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.[62]

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[58] DOI: 10.3390/waste1040050
[59] WorldFootwear 2019 YearBook
[60] https://tinyurl.com/mrys92ya
[61] https://www.ctcr.es/en/proyectos-3/2357-recalza-suelas-2
[62] https://www.vivobarefoot.com/us/blog/circ-partnership-launch

Despite these initiatives, the recycling of footwear, namely of soles and insoles, is still largely based in shredding and grinding the materials for reuse.[62,63] 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:**[64] 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:**[65] produce recycled rubber soles from recycled rubber from tires.

[63] US20110183559A1, Method for Recycling Waste Shoe Soles and a Laminate Made According to the Method
[64] https://vapesol.com/sustainable-recycled-soles/
[65] https://komrads.world/blogs/news/recycled-rubber-the-sole-of-our-products

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