HIGH PERFORMANCE BIO-BASED POLYMERS

STATE OF THE ART AND CHALLENGES IN ENDING PLASTIC WASTE

Prof. Debora Puglia
University of Perugia (IT)

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FURIOUS

THERMO FIRE

Circular Bio-based Europe Joint Undertaking

Bio-based Industries Consortium

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https://www.furious-project.eu/

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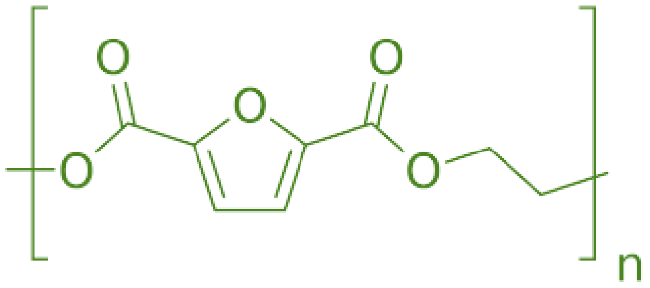
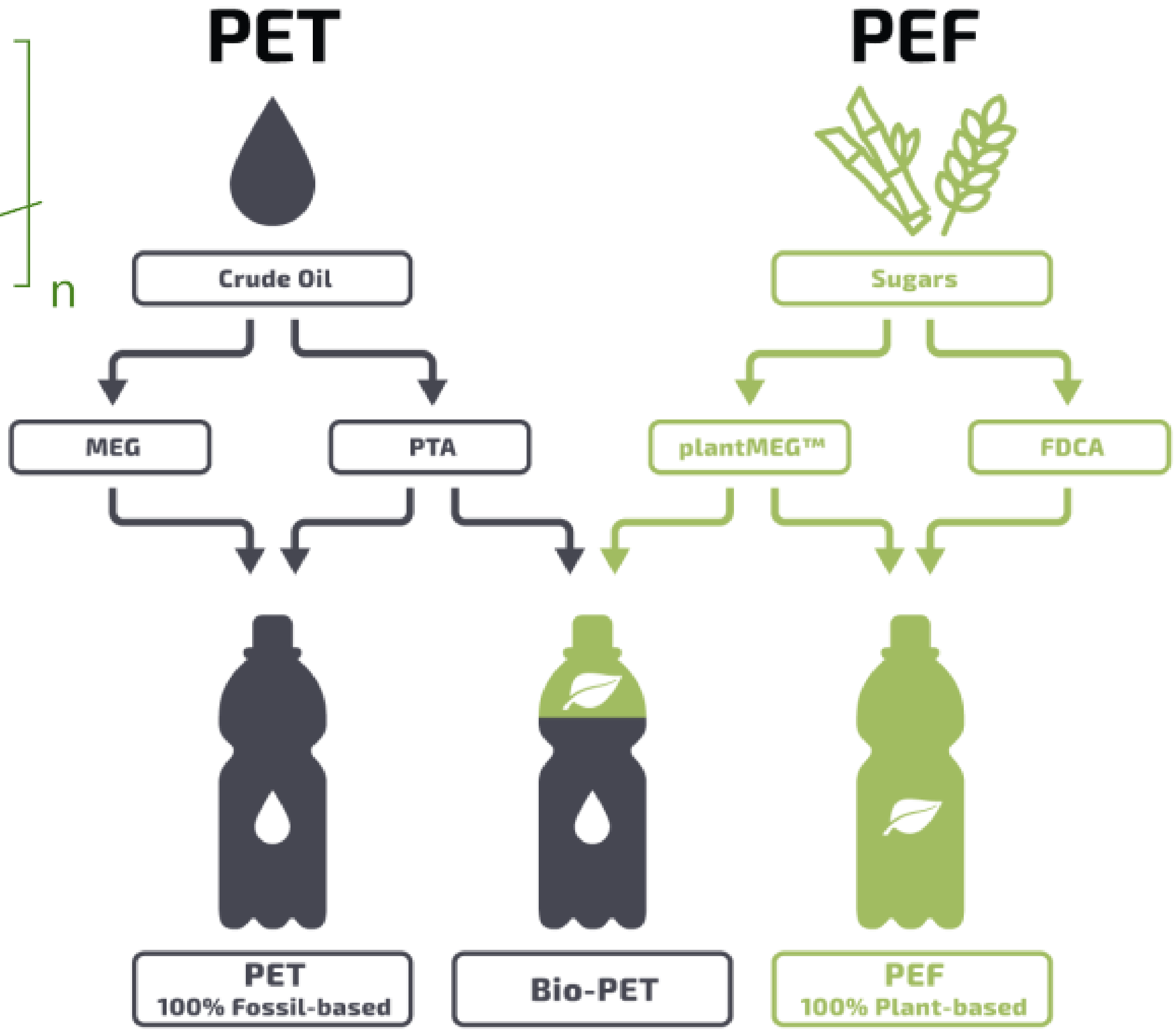
1 June 2023 - 31 May 2027

Why FURIOUS? - PEF and its BENEFITS

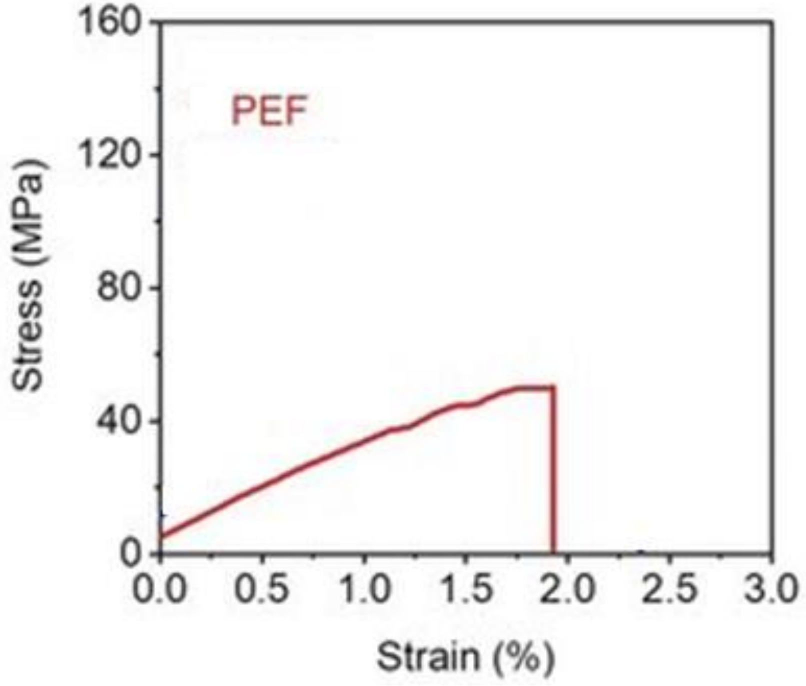


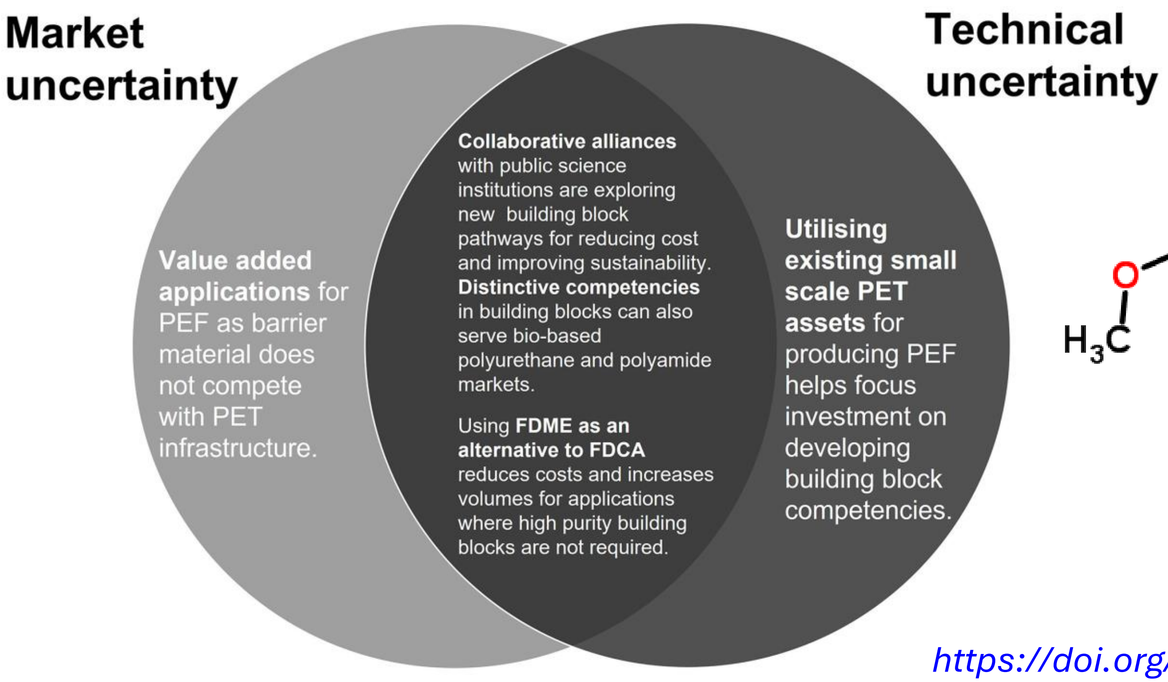


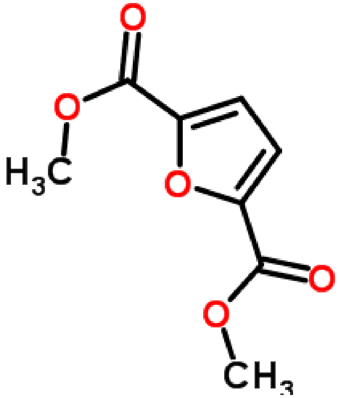
Polyethylene furanoate (PEF) benefits:

- superior thermal properties, including a **higher glass transition temperature** and **lower melting point** (compared to **PET)**
- barrier properties, including a **higher oxygen**, **carbon dioxide, and water barrier**, in comparison with PET
- PEF production from lignocellulosic biomass waste offers a sustainable and environmentally friendly alternative to conventional plastics, contributing to a circular bioeconomy

Why FURIOUS? - PEF and its DRAWBACKS







https://doi.org/10.1002/bbb.2438

- Poly(ethylene Furanoate) (PEF), is ***basically stiff** and **fragile***, which strongly limits its applications in sectors far from the rigid packaging
- Additionally, limited information is available on the **processability of this new class of polymers** with respect to conventional polymer processing techniques
- PEF chemistry needs to be deeply revolutionized, opening new perspectives in the synthesis of new polyesters with **ADAPTIVE properties** to satisfy identified application sectors with **STRINGENT operative conditions**

Why FURIOUS? – FDCA unique characteristics

FuraCore®
by Stora Enso

https://www.youtube.com/watch?v=GAa6g0ZOnsw

- **advancement in the synthesis** of new biopolymers by developing **sustainable processes (homopolymerization, copolymerization, reactive blending)** and designing versatile materials for a range of demanding applications;

- Investigating the **suitability for processing** of the new materials using **"STANDARD" (injection moulding, cast/blow extrusion)** and **"UNCONVENTIONAL"** methods **(electrospinning, stereolithography)**;

- Assessing the **recyclability, compostability** and **biodegradability** of the materials with a view to reducing waste and ***promote re-polymerization (by using gamma radiation pre-treatment)***;

- Evaluation of the **economic and social viability** of the processes and products;

- Intriguing physical/mechanical, oxygen and vapor barrier properties of new **furan-based polyesters** make them the ***MOST CREDIBLE ALTERNATIVE*** to conventional plastics (and **PEF** alternative)

Prospects for market deployment

6 innovative prototypes based on bio-based materials:

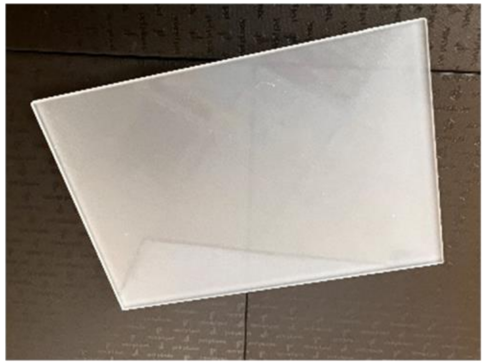
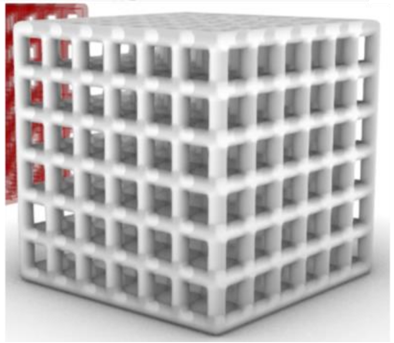
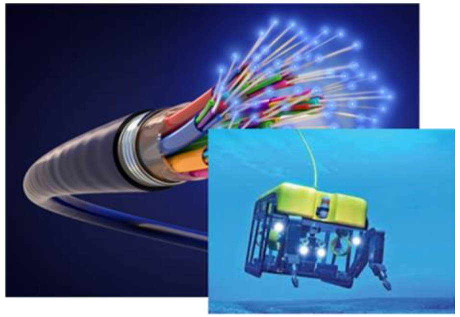
i) **2 films for the Biomedical (flexible) and Electronic Packaging (rigid)** with high barrier properties, *easy sterilization* and *mechanical recycling*;

ii) **1 electrospun filter** and **1 injection molded screen** for automotive applications with **intrinsic antibacterial properties and high resistance to UV weathering**;

iii) **1 3D printable photoreactive sensor** and **1 elastomeric degradable cable** for underwater applications**;**

iv) **polymeric** prototypes with **up to 30% GHG emissions reduction** than currently used materials

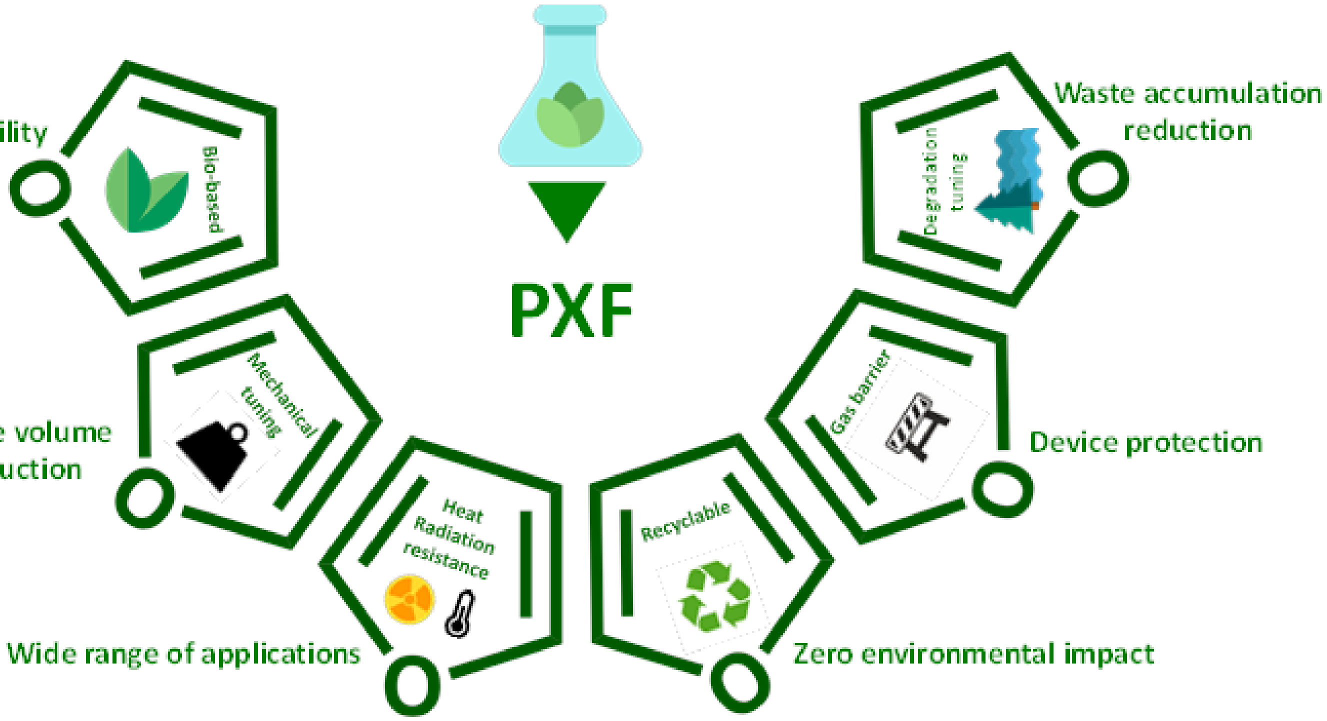


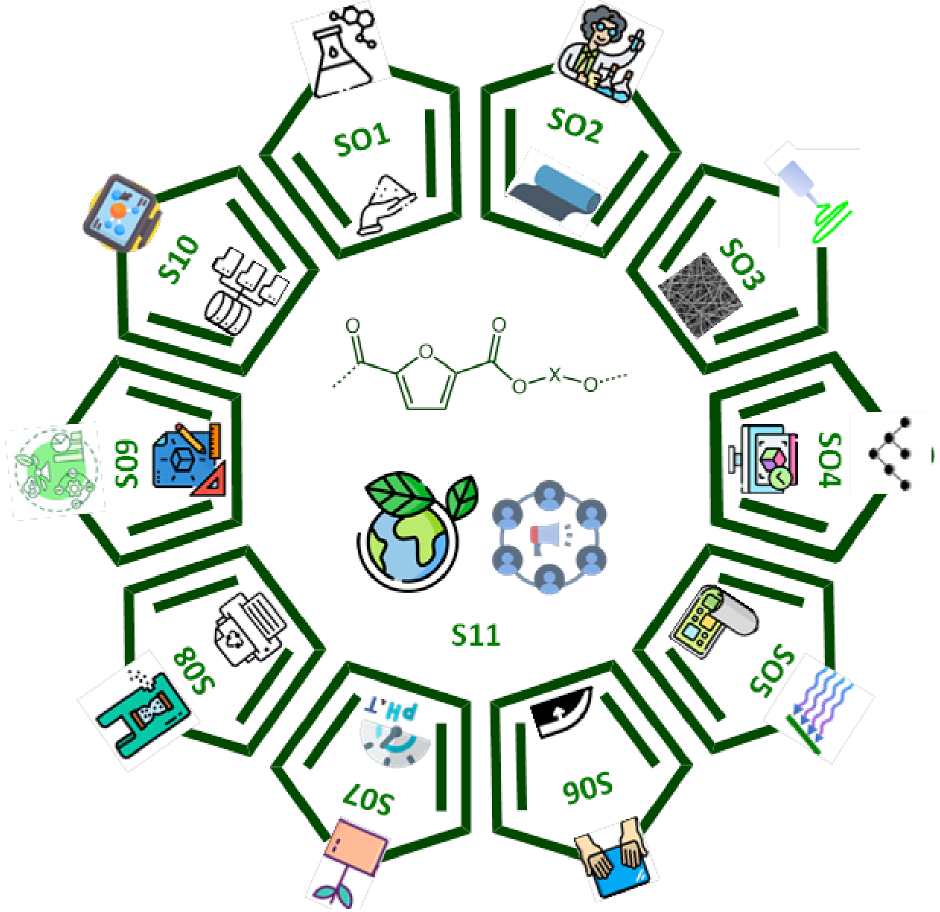





FURIOUS - Beyond State of Art

SoA	FURIOUS
- PE, PU, PS, PVC (widely used in blisters) (**poor resistance to aging with loss in mechanical properties, crosslinking phenomena and discoloration**) - Electronic components and circuit boards require protection from humidity, extreme temperatures, mechanical loads and chemical effects, dielectric integrity	**compostable and/or mechanically recyclable formulations** able **to sustain γ radiation exposure**, **humidity** and **oxygen**. → 2,5-FDCA based polyesters synthetized by **tuning crystallizing ability and hydrophilicity**, can withstand higher barrier properties to gases and radiation.
- functional antimicrobial effect is often obtained by **coating and/or by incorporation of metallic (Ag) and metal oxides** (TiO_2, ZnO, CuO, SnO_2) during melt-spinning - PEF UV degradation showed significant discoloration, as well as evidence of both crosslinking/chain extension and chain scission	→ **inherent antibacterial property** linked to the presence of long side chains possibly containing sulphur atoms: **absence of antibacterial coatings or nanoparticles** will help to validate the option of chemical recycling and **further reprocessing of solubilized filters** at their end of life.
- **non-biodegradable plastics (e.g. polypyrrole, PVP) that have limited processability to mimic constructs** already applied in biomedical applications. - **photosensitive AM landscape is dominated by either very stiff polymers (e.g. PMMA) or soft ones (e.g. hydrogels).**	→ rational *ad hoc* designed changes in the polymer chemical structure (by **insertion through copolymerization of C=C double bonds** along macromolecular chain), **light printable FURIOUS polyesters** will be realized, quickly fabricated into complex porous structure, using a single polymer platform, by bringing at the same time diverse degradation kinetics.

FURIOUS - Objectives





Advancement in the **synthesis of new polymers from 2,5-FDCA with distinct and versatile structures**, by generating at the same time **valorised products to be applied in demanding sectors** by pursuing **Strategic Objectives**

Strategic objectives

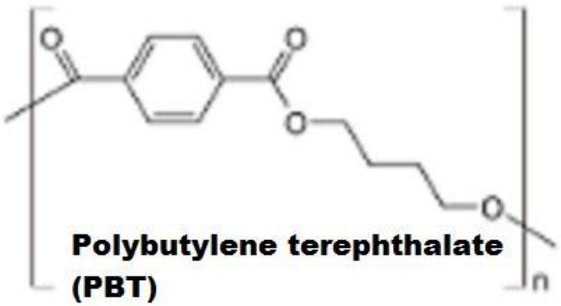
FURIOUS

SO1: Development of 2,5-FDCA monomer at high purity

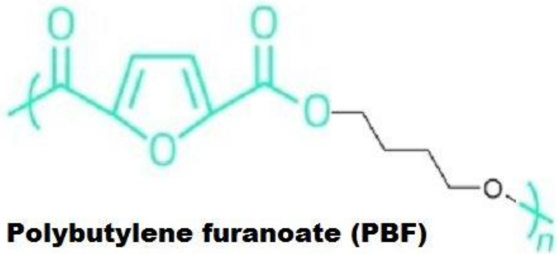
- **high purity** (**> 99.8 %**) - tested with a **reference polymer (PBF)**
- **Derivatizing procedures** of 2,5-FDCA into the corresponding ester (**acid catalysed esterification**) optimized to make the process cost effective for high-volume/mass production

SO2: Development of flexible and rigid 2,5-FDCA based polyesters

- **HOMOPOLYMERS** route
- **COPOLYMERIZATION** to get a family of **new** 2,5-FDCA-based random copolymers.
- process parameters and physico-chemical/engineering features of the achieved polyesters will be collected in an **open-access database** (easy-to-use design tool) for any future application



Polybutylene terephthalate (PBT)



Polybutylene furanoate (PBF)

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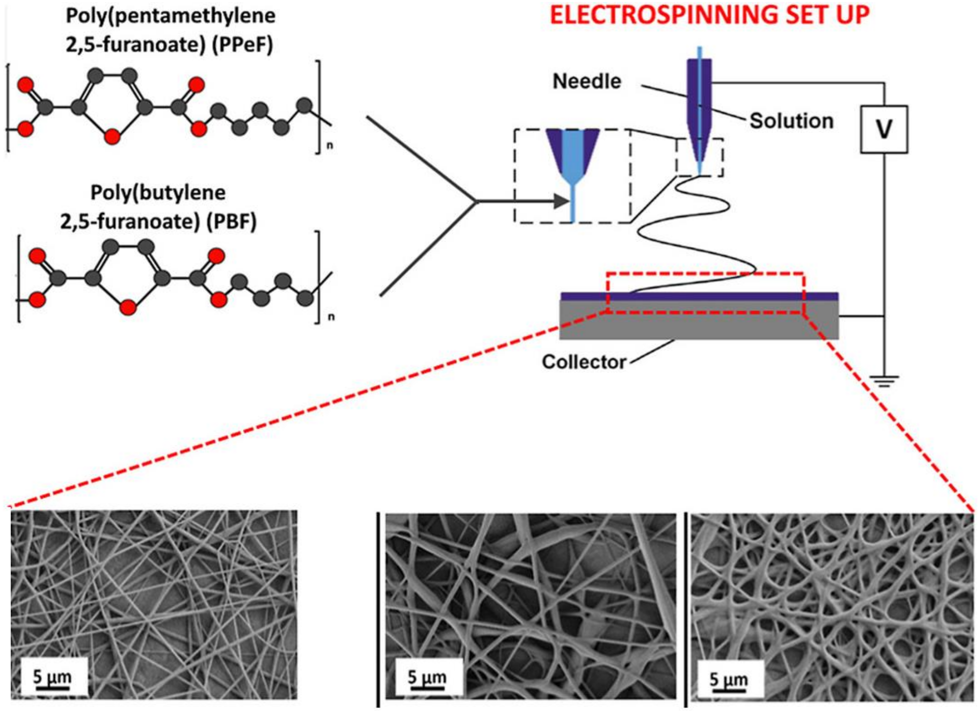
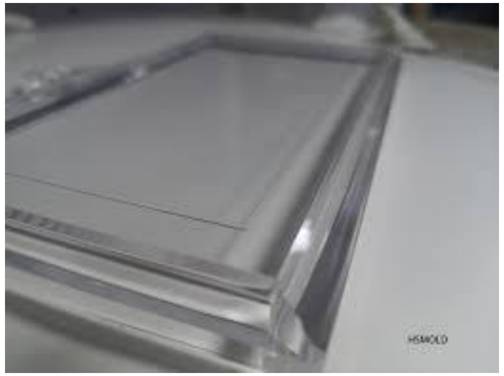
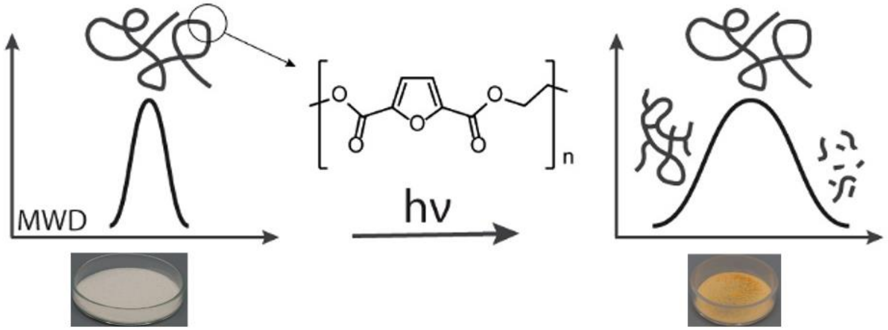
Strategic objectives

SO3: Development of injection mouldable and electrospinnable 2,5-FDCA-based polyesters

Development of **2 novel furan-based polyesters** having **tuneable processability (both in melt and solution)**, suitable for the automotive sector that requires materials with **inherent antibacterial functionality** and polyesters with high **resistance to UV weathering**





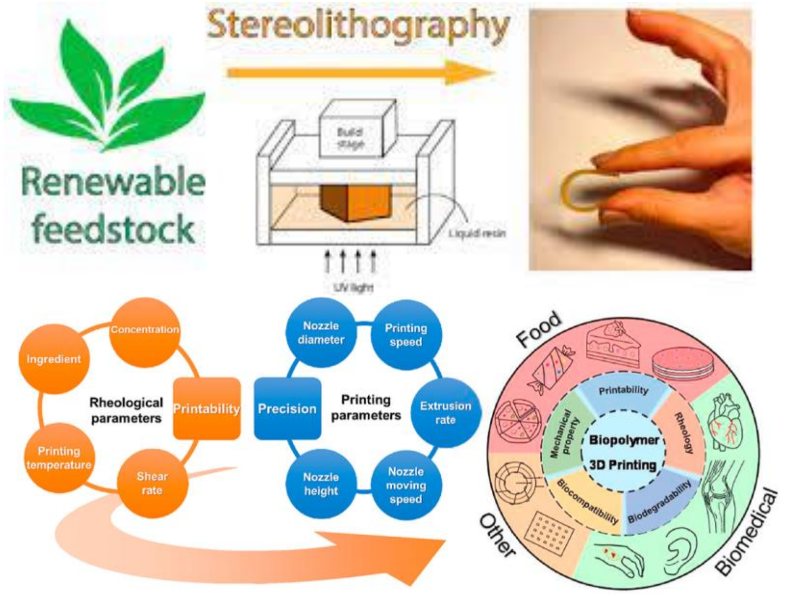


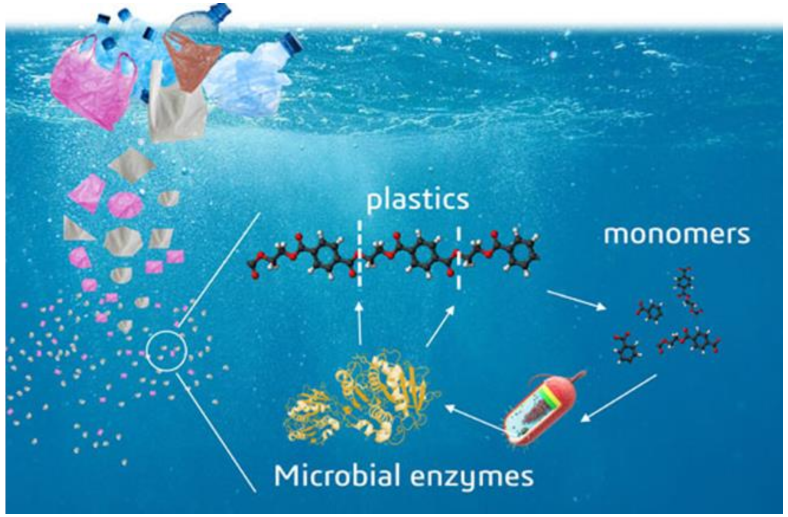
Strategic objectives

SO4: Development of 3D-printable and UV crosslinkable 2,5-FDCA-based polyesters

Development of **2 novel furan based polyesters:**

1) furan based polymer able to interact with **light** and **processable by stereolithography** and **3D printing**, to match the request of a sensor with **defined porosity**.
2) soft, hydrophilic and biodegradable elastomer for a probe coating: **transparency** and **controlled biodegradability** of the second furan polyester material will be considered to identify flexible anchoring systems in non-structured subsea environments.

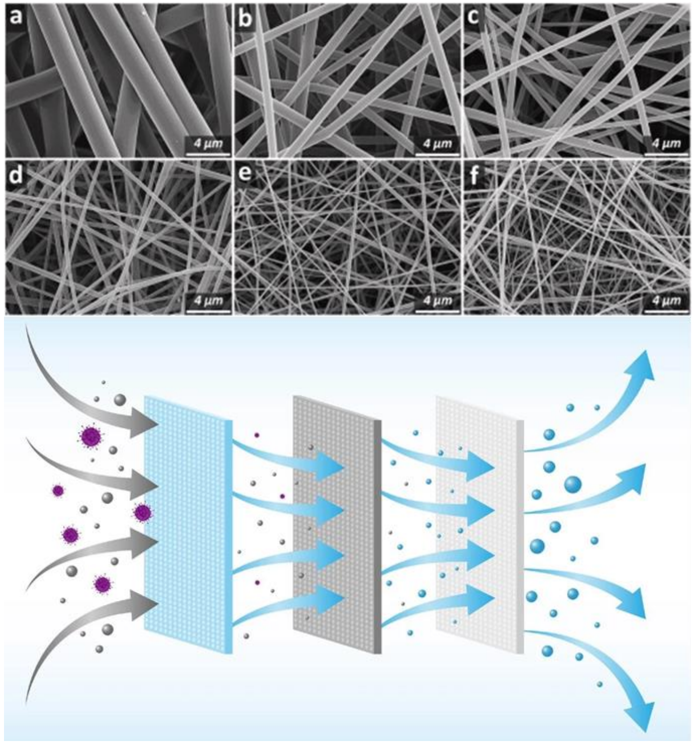


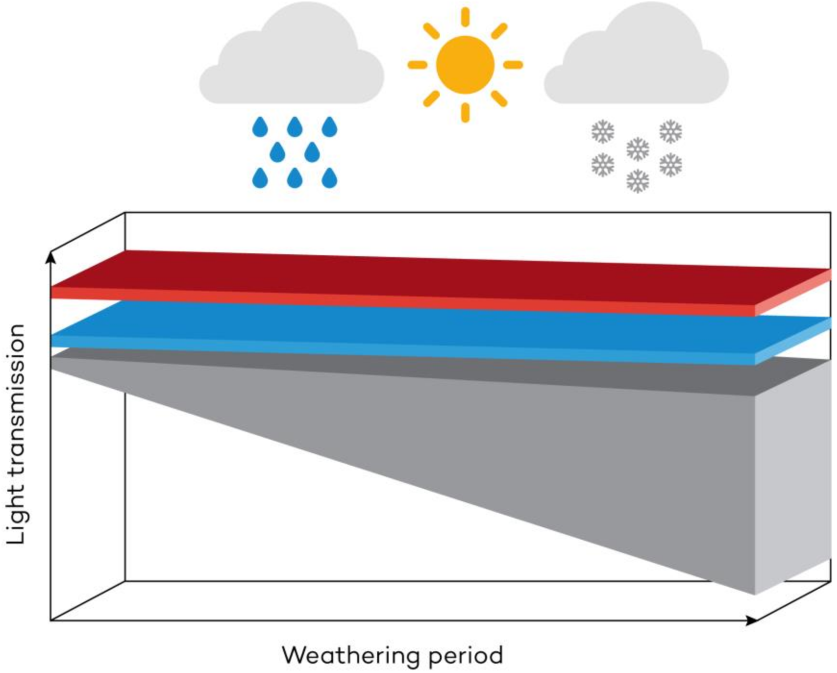


Strategic objectives

SO5: Validation of inherent antibacterial electrospun filter and high transparent, resistant to UV weathering injection moulded screen for automotive applications

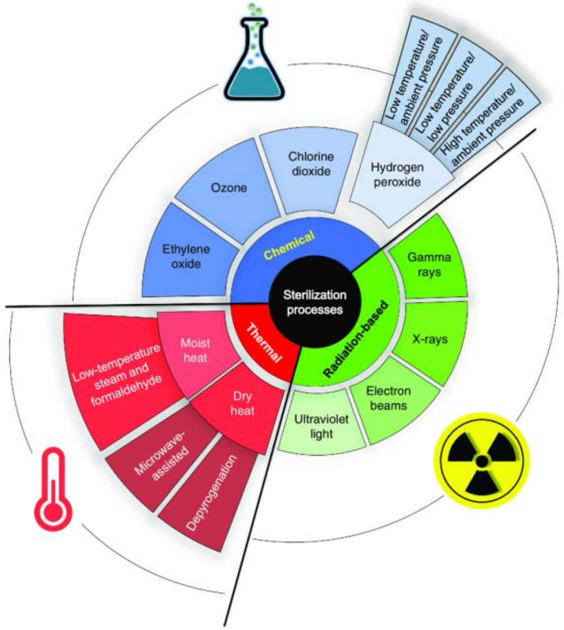
- filtering activity coupled to **antimicrobial effect and exposure to UV weathering/detergents**
- combining enhanced material properties (injection mouldable and electrospinnable 2,5-FDCA-based polyesters developed as SO3) and the selection of well-established injection moulding technique with electrospinning still not validated with furan-based polyesters.

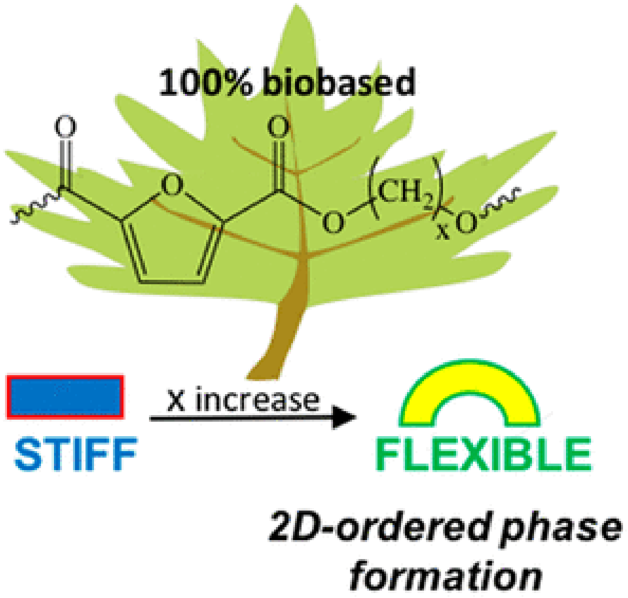


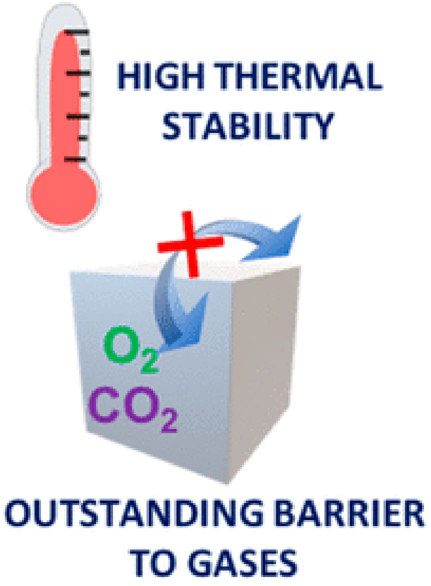


SO6: Validation of high gas and water barrier, gamma ray resistant films for biomedical and electronic packaging applications

- *simulate real sterilization and exposure to oxygen conditions*
- **selection of extrusion/film forming processing procedures still not validated** in the case of **flexible 2,5-FCDA-based polyesters** and partially optimized for rigid packaging.
- barrier to oxygen and moisture







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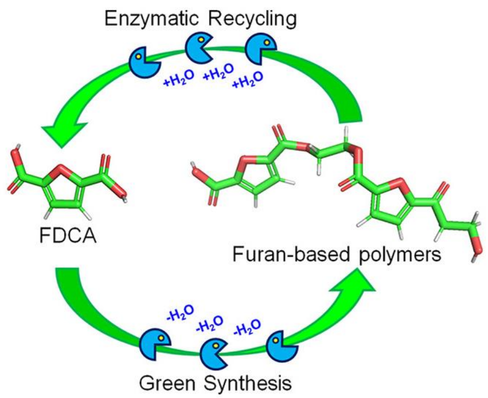
SO7: Assessment and validation of mechanical recyclability, enzymatic depolymerization, chemical de- and re-polymerization, compostability, biodegradability of end-use materials

Enzymatic degradation investigated as the most eco-friendly recycling process for those systems where they could represent a solution to the circularity (**biomedical and electronic packaging**).



Chemical degradation promoted by **ionic liquids and deep eutectic solvents** will be also investigated as an alternative to processes that involve use of volatile organic compounds (filter for automotive).

Compostability will be also evaluated, representing a better choice in the case of FURIOUS materials obtained by **melt blending two polymers.** Additionally, more specific biodegradability studies (**hydrolytic degradation in presence of salts and microorganisms in the seabed**), essential in the case of underwater application, will be considered for proposed FURIOUS materials to validate this specific EoL option.

Mechanical recyclability will be indeed verified for those applications in **AUTOMOTIVE** that can bear **reprocessability both in melt (in case of failure, as in the case of a screen)**

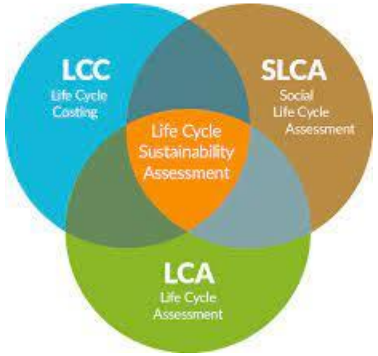
Strategic objectives

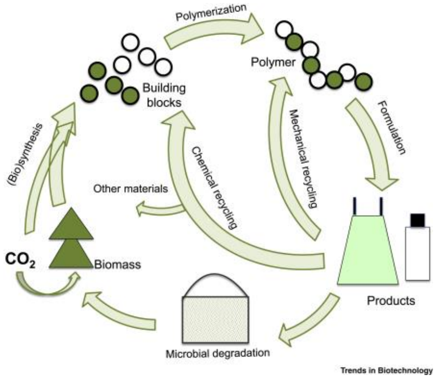
SO8: Assessment of the environmental, economic and social viability of procedures/products

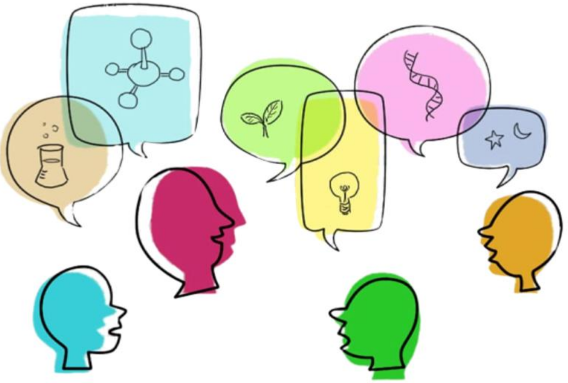
- environmental, economic and social impacts by LCA, LLC, and s-LCA.
- objective is to obtain highly pure 2,5-FDCA monomer, versatile polymers and **outstanding end products with better LCA/LCC results in comparison to the current counterparts** in the market.

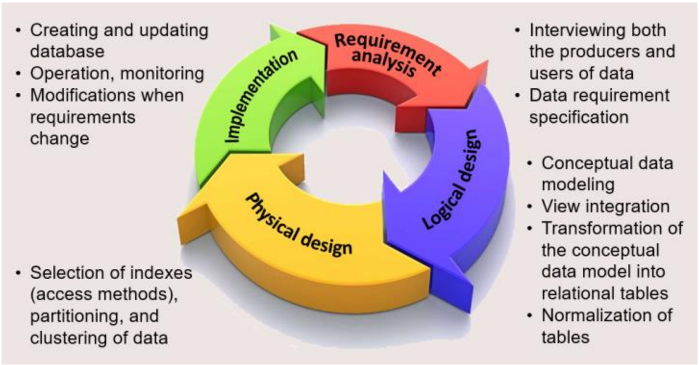
SO9: Creation of a Sustainable by Design Database for the elaboration and management of project data

SO10: Maximization of Communication, Dissemination, and Exploitation strategies









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