



**Biomass  
Biorefinery  
Network**

## **4<sup>th</sup> BBNet Conference**

**The future prospects for biorefining:  
Feedstocks, technologies and products**

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# Bug-Busting Spandex

**4<sup>th</sup> BBNet Conference**

**15-17<sup>th</sup> October 2025**

Helen C. Hailes

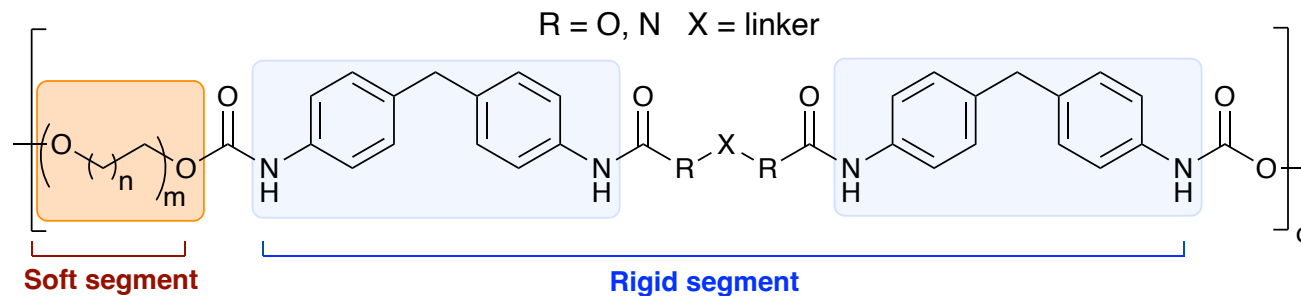
Department of Chemistry, University College London





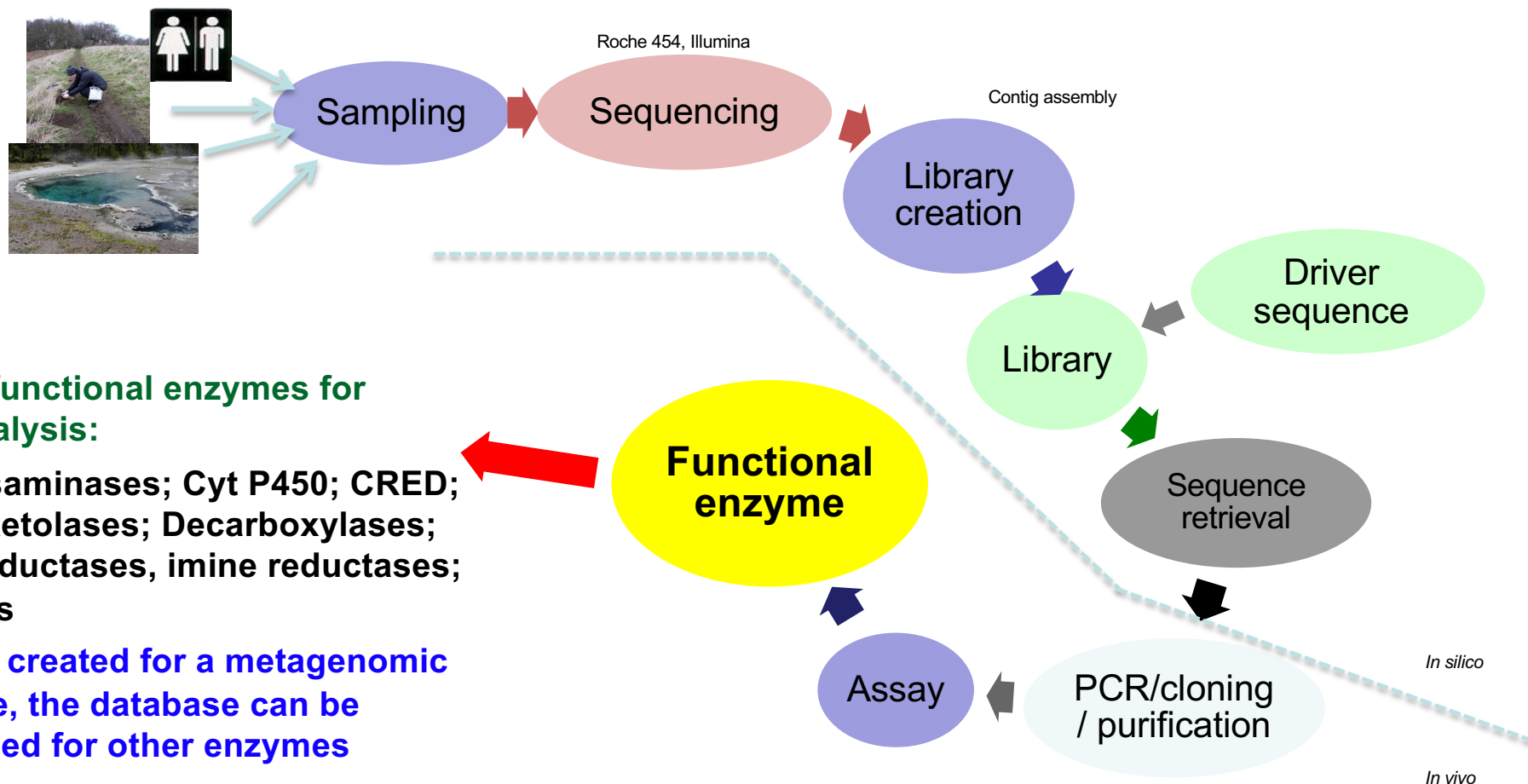
- Type of **synthetic fabric** (aka elastane and Lycra)
- It is found in almost all **stretchy clothing** (e.g. gym wear, soft winter knitwear etc, stretchy jeans)
- It is often blended with PET or nylon, or also viscose, cotton etc
- Many different mixtures are sold but the key element is an aromatic diamine unit with carbamate linkers.

## Spandex



# New Enzymes: Functional Metagenomics

## - Isolation of genes from organisms in an environment



## - New functional enzymes for biocatalysis:

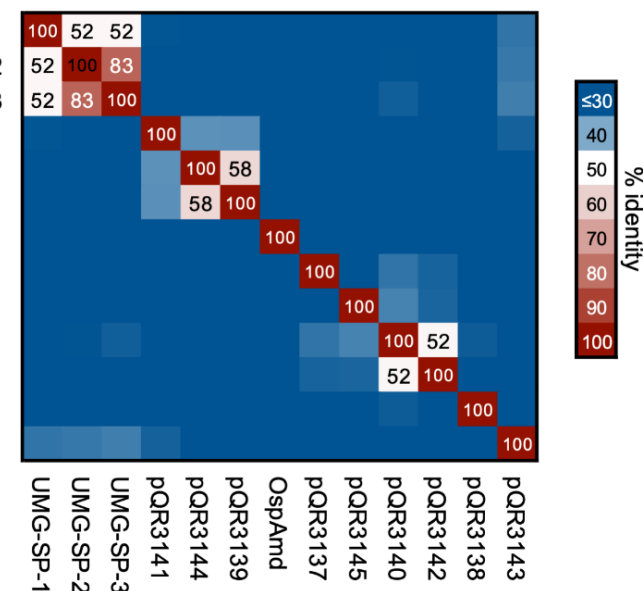
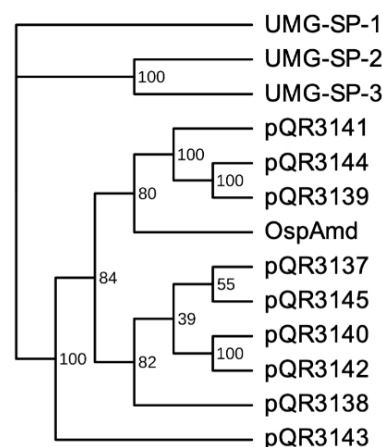
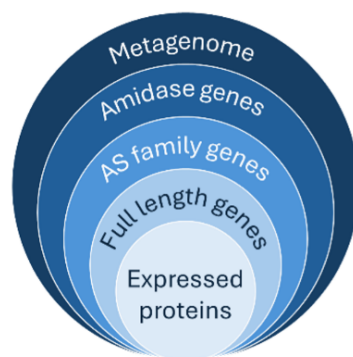
- Transaminases; Cyt P450; CRED;  
Transketolases; Decarboxylases;  
Ene-reductases, imine reductases;  
PUases

- Once created for a metagenomic sample, the database can be searched for other enzymes



# Drain metagenome mining

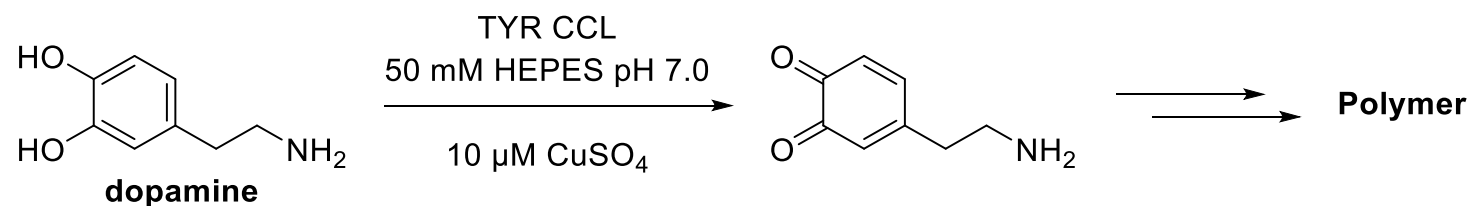
- Drain metagenome – a protein rich environment
- Amidases – searched for novel amidase signature (AS) family
- Conserved Ser-Ser-Lys catalytic triad – retrieved ORFs from drain metagenome
- Cloned + expressed
- UMG-SPs + OspAMD



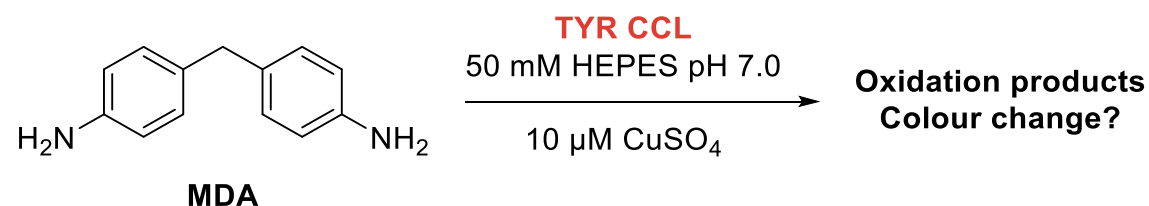
S. Anselmi *et al.*, *Green Chem.*, **2025**, 27, 12176; Y. Branson *et al.*, *Angew. Chem. Int. Ed.*, 2023, **62**, e202216220; L. Pastor *et al.*, *ChemSusChem*, 2025, e202500662

# Enzyme assays

- Aim - high-throughput capability
- Tyrosinases oxidise e.g. tyrosine and dopamine

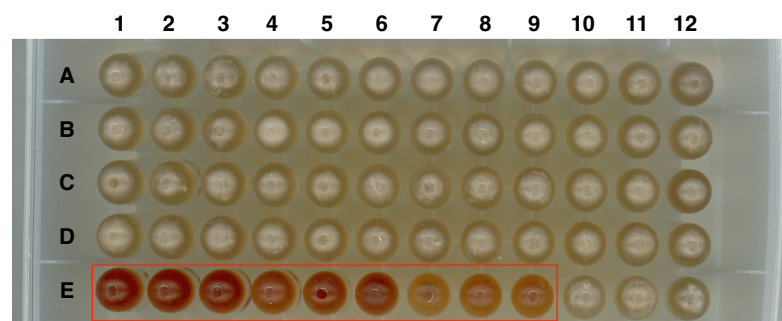
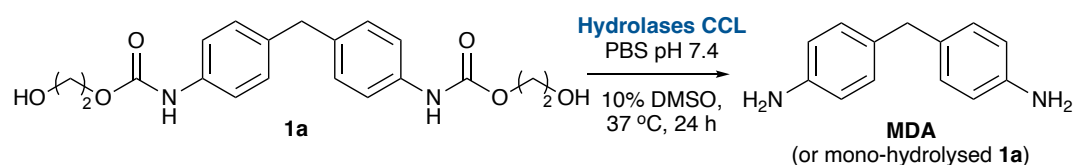


- Tested tyrosinases with MDA

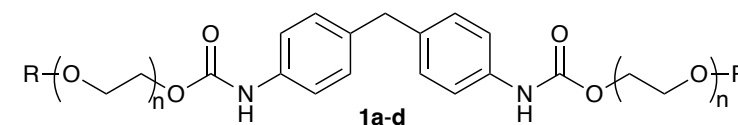


# Assay validation

- Tested assay after treatment of a model compound against PETases, nylonases, PLAses and recently reported PUases



**RsTYR CCL**  
(5.0 mg mL<sup>-1</sup>)  
10 μM CuSO<sub>4</sub>  
18 h

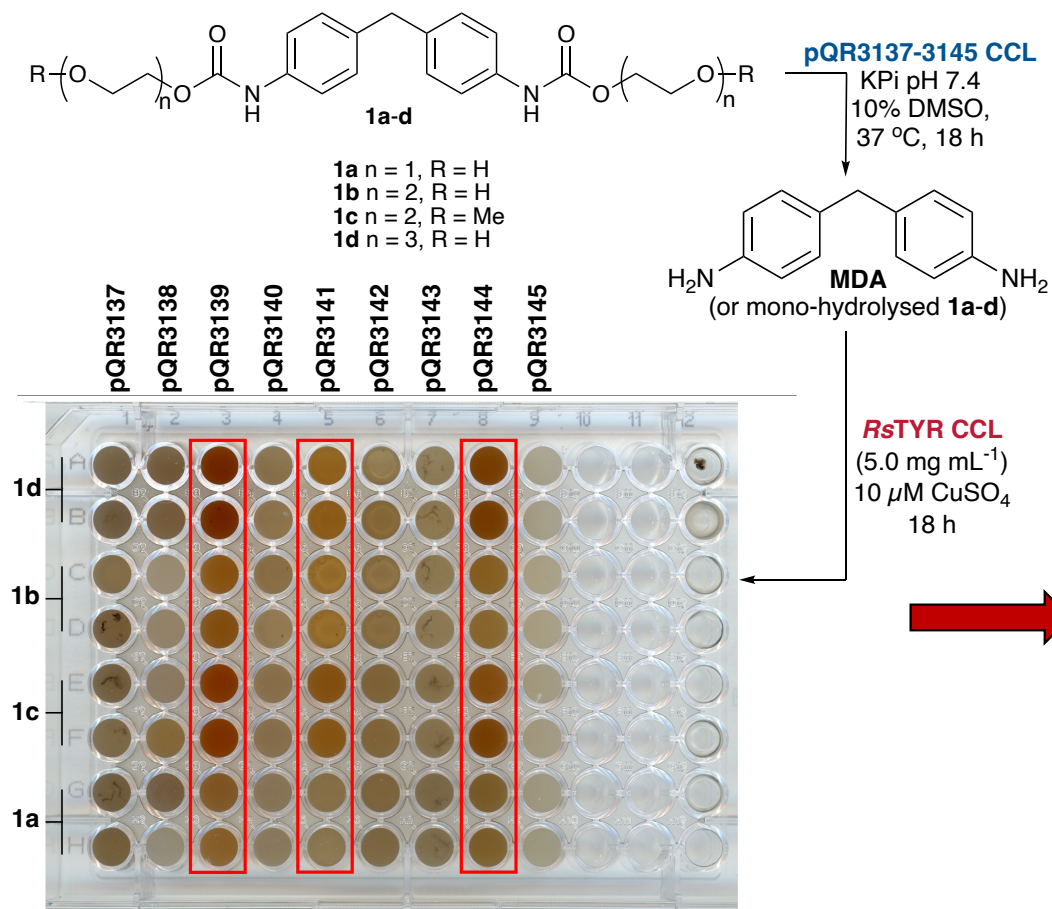


**1a** n = 1, R = H  
**1b** n = 2, R = H  
**1c** n = 2, R = Me  
**1d** n = 3, R = H

| Enzyme | Substrate | Conv. % |
|--------|-----------|---------|
| EVC    | <b>1a</b> | 2       |
| EVC    | <b>1b</b> | 19      |
| EVC    | <b>1c</b> | <1      |
| EVC    | <b>1d</b> | 10      |

- Confirmed by HPLC – MDA detected in E1-9 only
- Several spandex analogues synthesised and EV controls

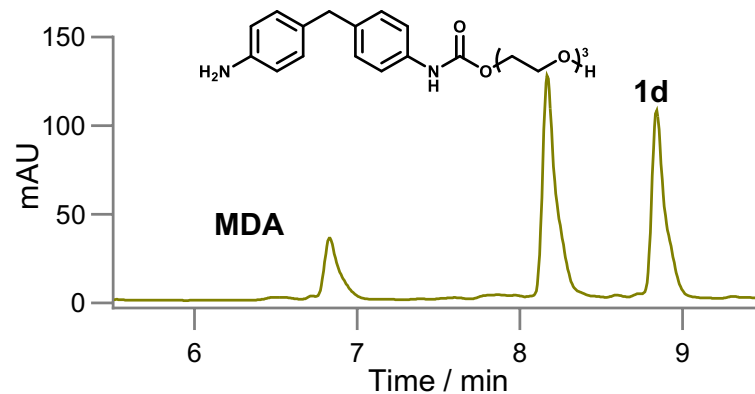
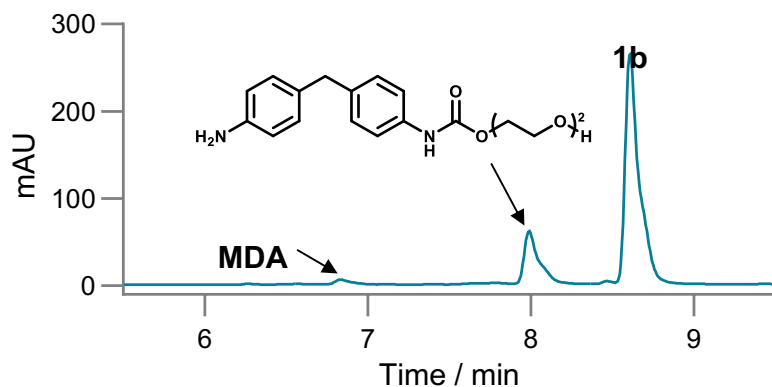
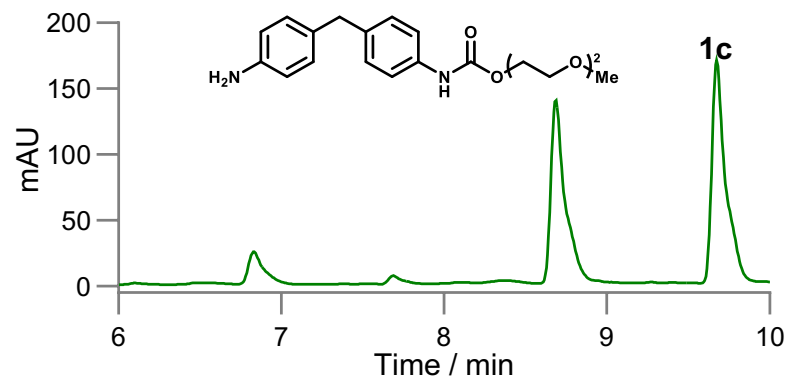
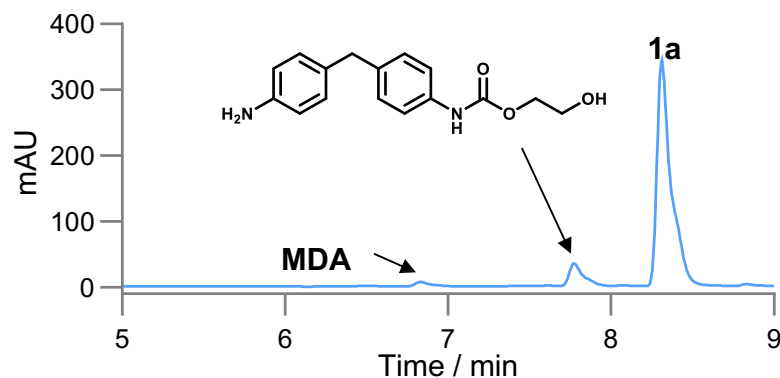
- The metagenomics enzymes were screened



| Enzyme  | Substrate | Conv. % | MDA yield % |
|---------|-----------|---------|-------------|
| pQR3139 | 1a        | 9       | 3           |
| pQR3139 | 1b        | 29      | 4           |
| pQR3139 | 1c        | 58      | 13          |
| pQR3139 | 1d        | 69      | 17          |
| pQR3141 | 1a        | 6       | <1          |
| pQR3141 | 1b        | 38      | <1          |
| pQR3141 | 1c        | 55      | 1           |
| pQR3141 | 1d        | 49      | 1           |
| pQR3144 | 1a        | 25      | 2           |
| pQR3144 | 1b        | 28      | 2           |
| pQR3144 | 1c        | 63      | 14          |
| pQR3144 | 1d        | 69      | 15          |

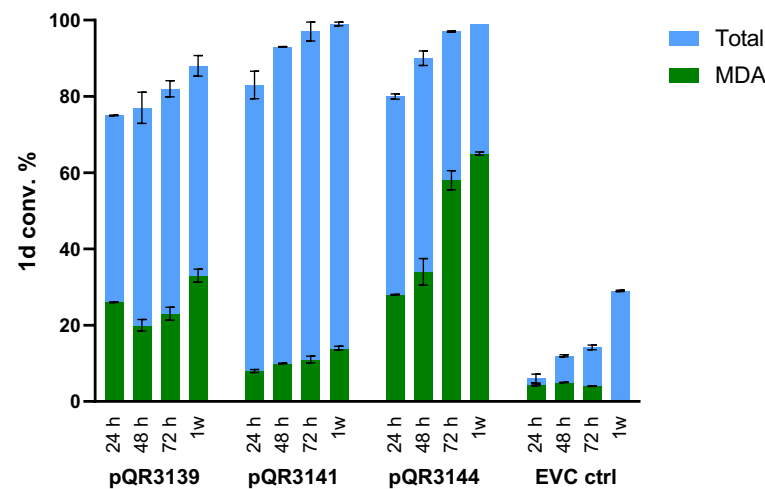
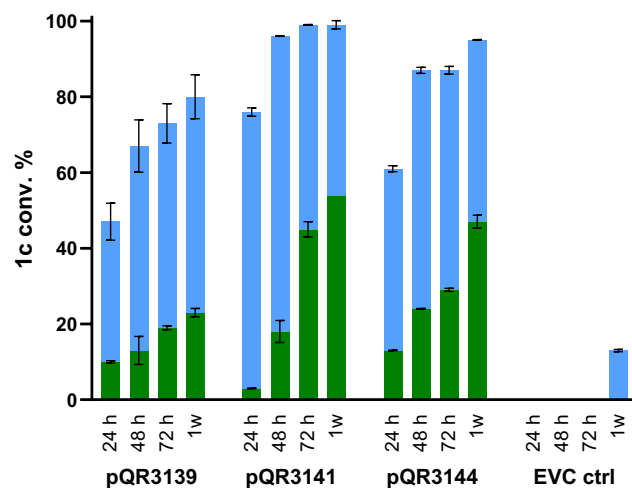
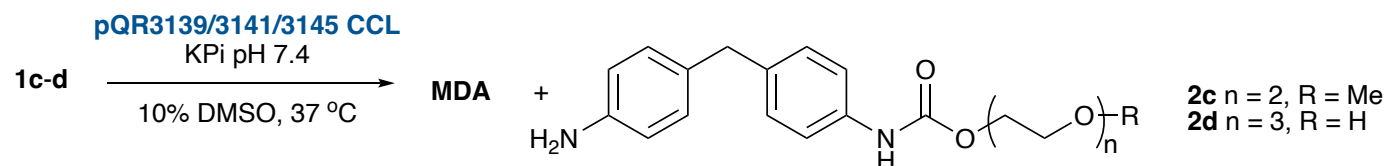
# Assays - two products formed

- Mono-products also formed e.g. pQR3189





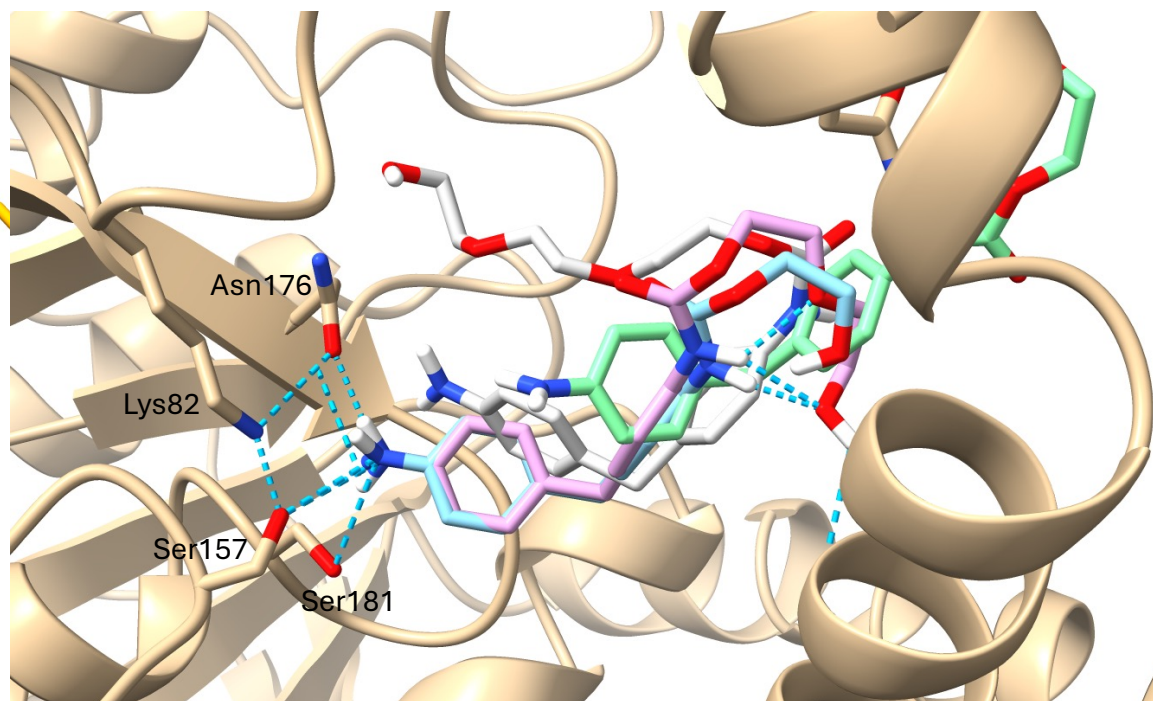
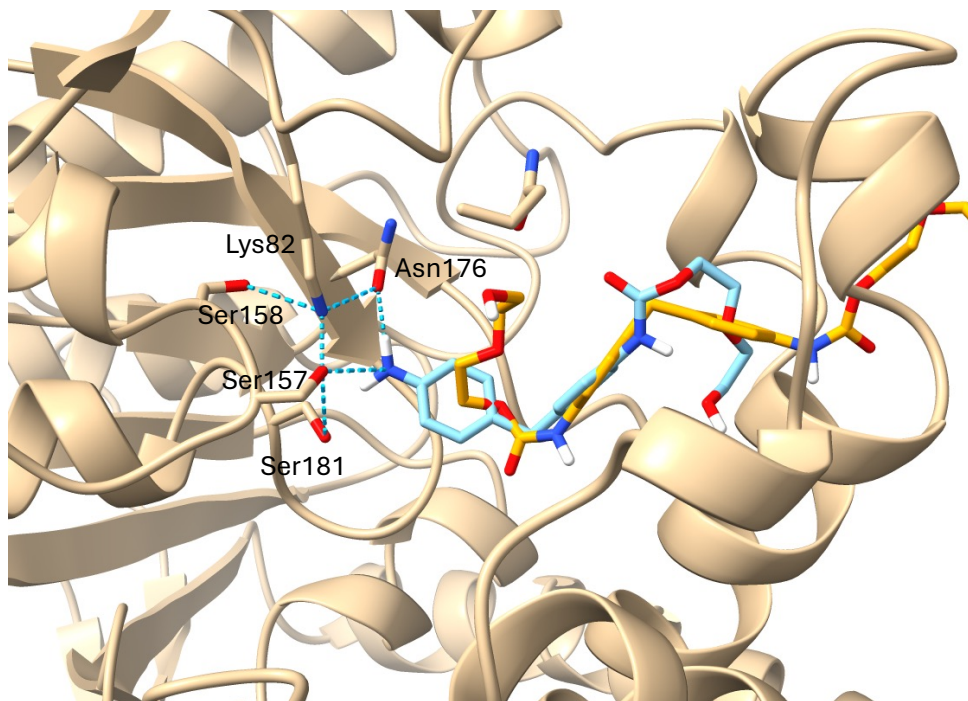
# Time-course study



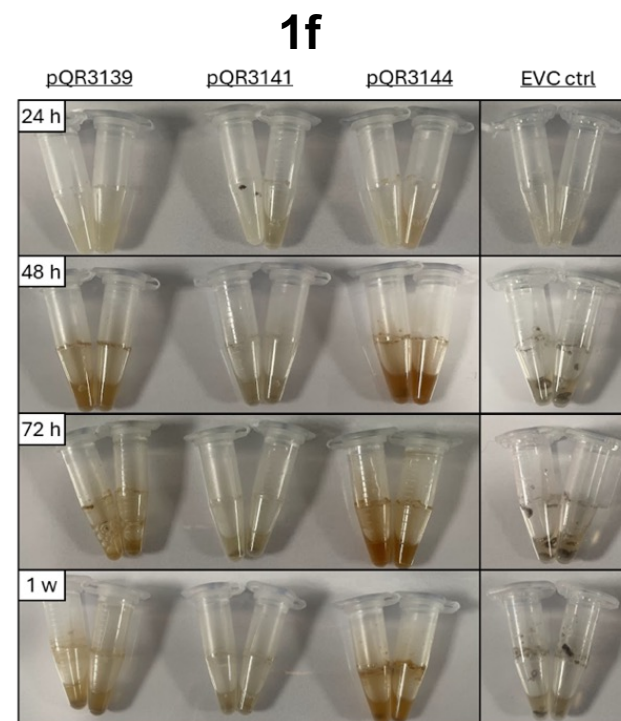
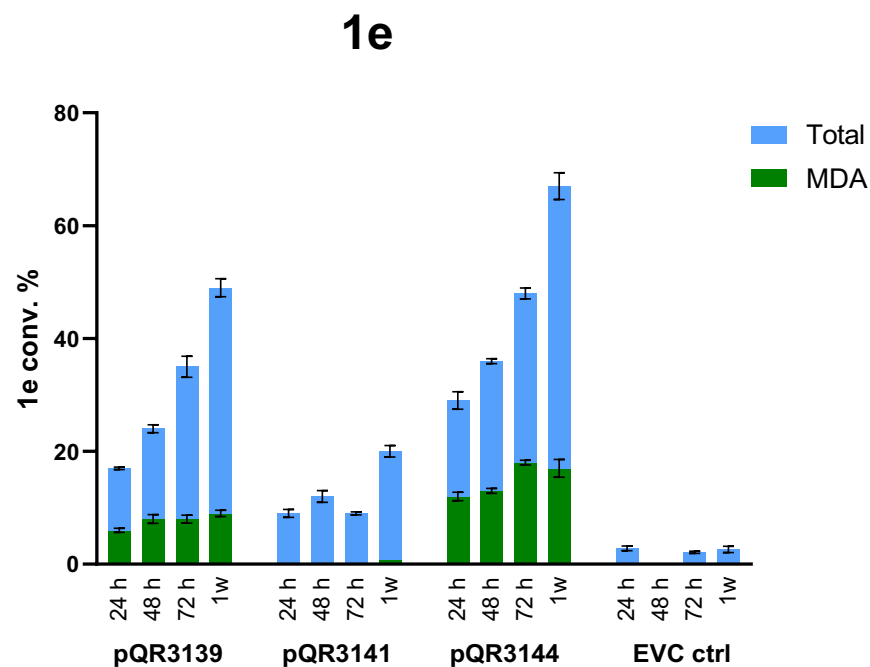
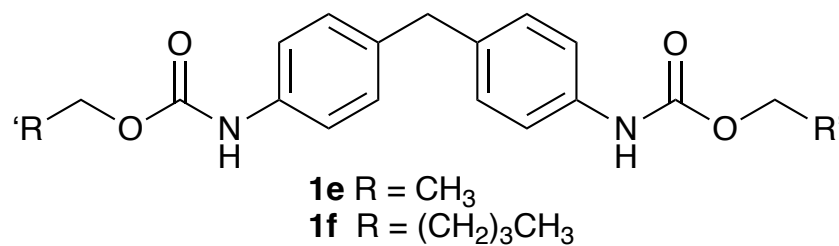
- pQR3144 less MDA generated

- **1b** (orange) and **2b** (cyan)

- **2a** cyan, **2b** pink, **2c** grey, **2d** green
- **2a** & **2b** bind further into the active site



# Less soluble substrates

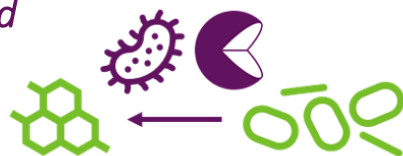


# The P3EB Mission Hub



- *Preventing Plastic Pollution through Engineering Biology (P3EB) Mission Hub*

3. Engineered enzymes and microbes for upcycling to higher-value products



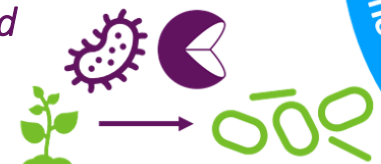
Upcycled Chemicals

2. Engineered enzymes for efficient plastics deconstruction



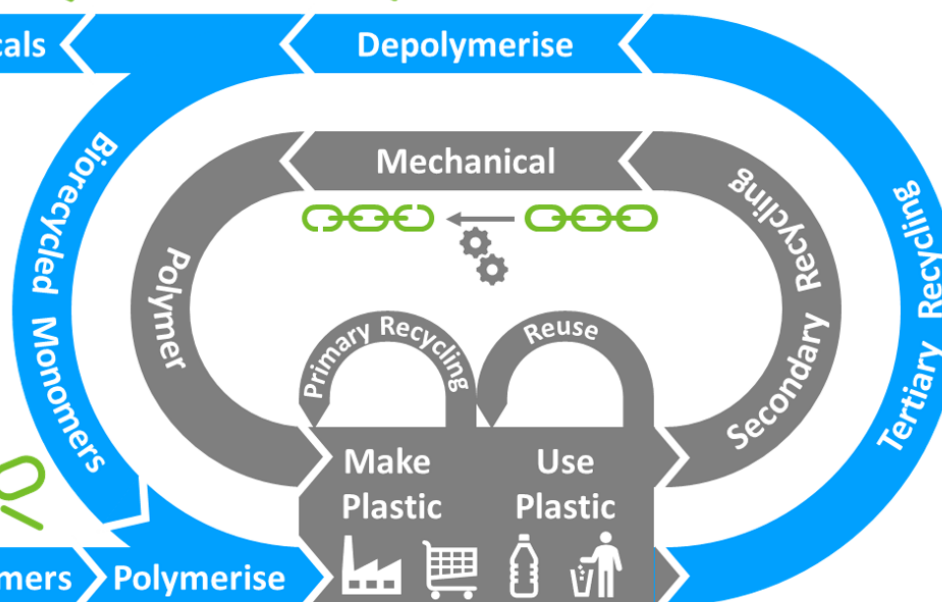
Depolymerise

1. Engineered enzymes and microbes for sustainable monomer production



Sustainable Monomers

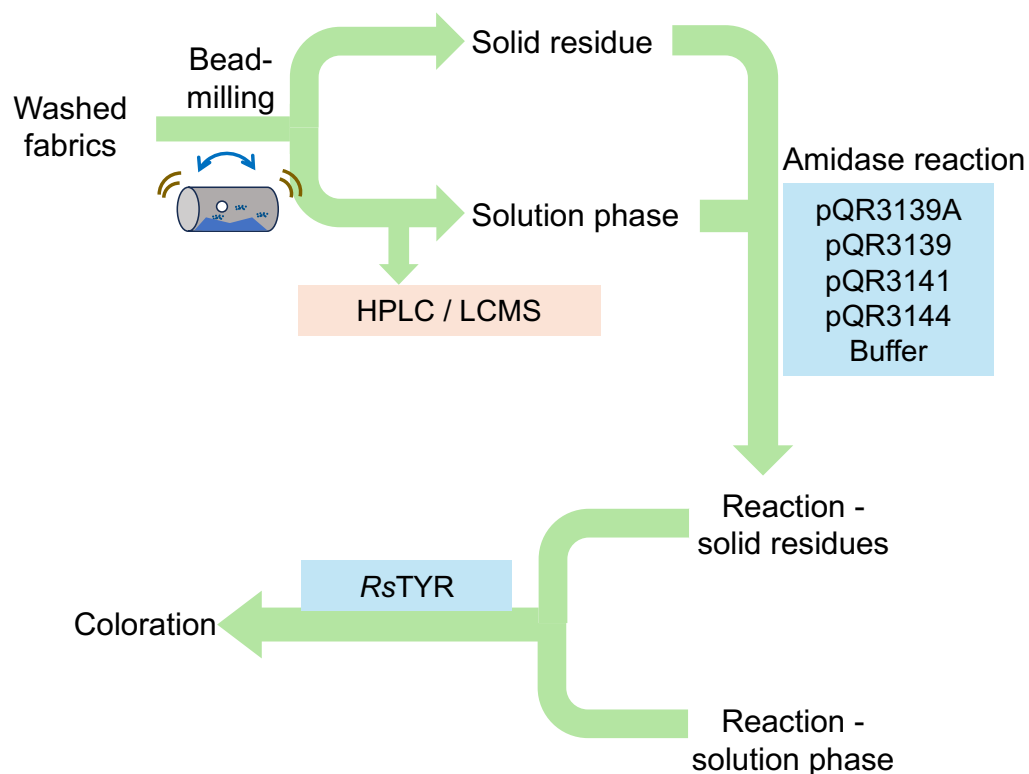
Polymerise



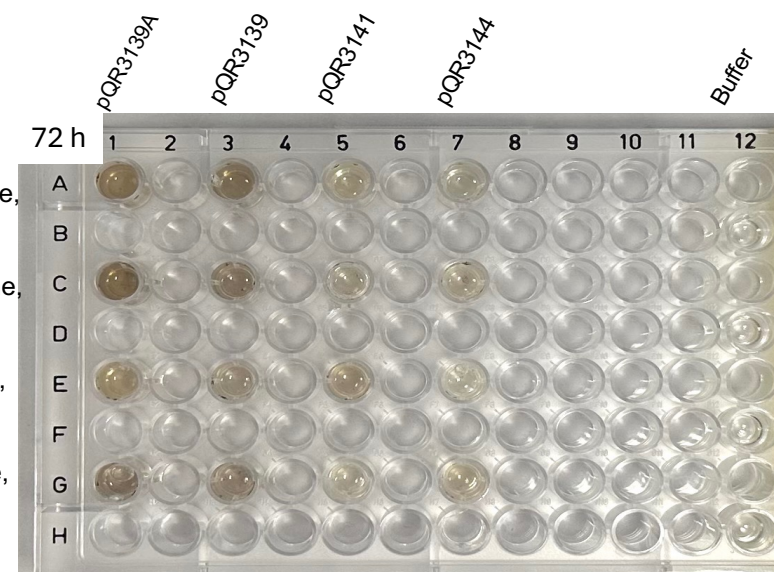
- *Our Mission:* to support the transition towards a circular plastics economy.

# What about with commercial textiles?

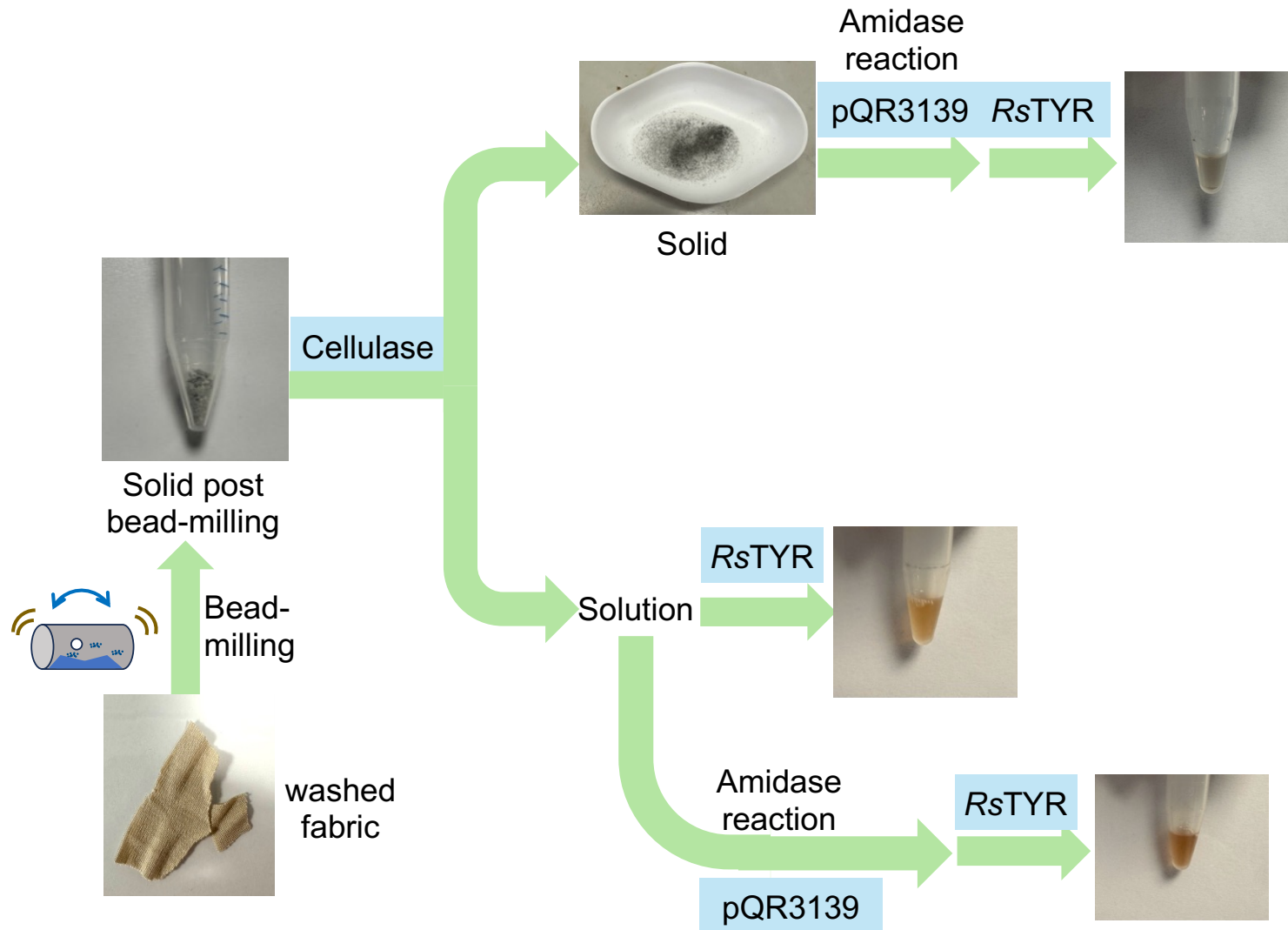
- Textiles containing **95% viscose/5% spandex** and **96% cotton/4% spandex**



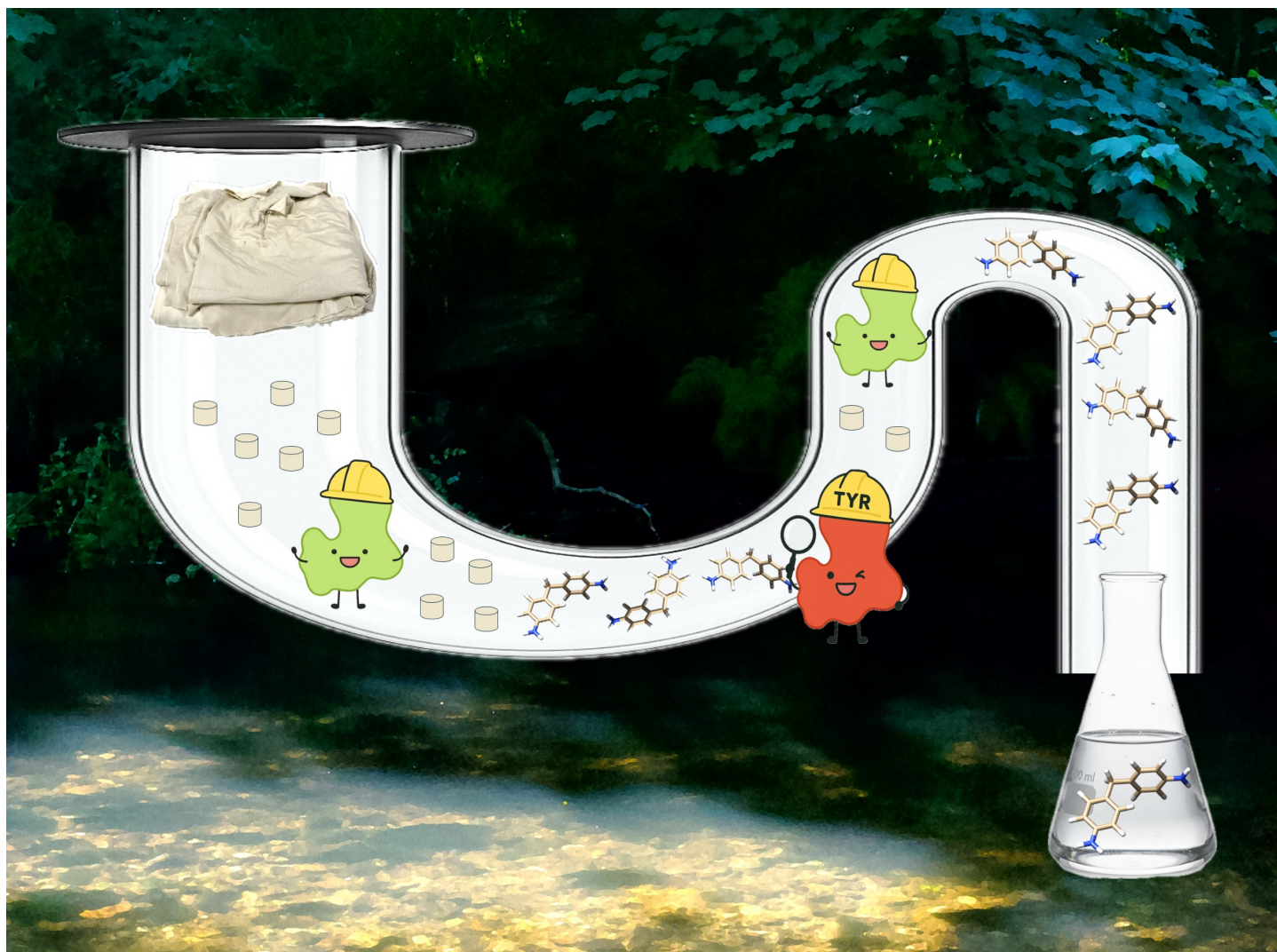
A : viscose elastane, MeOH layer  
 C : viscose elastane, solid residue  
 E : cotton elastane, MeOH layer  
 G : cotton elastane, solid residue



# Further textile experiments



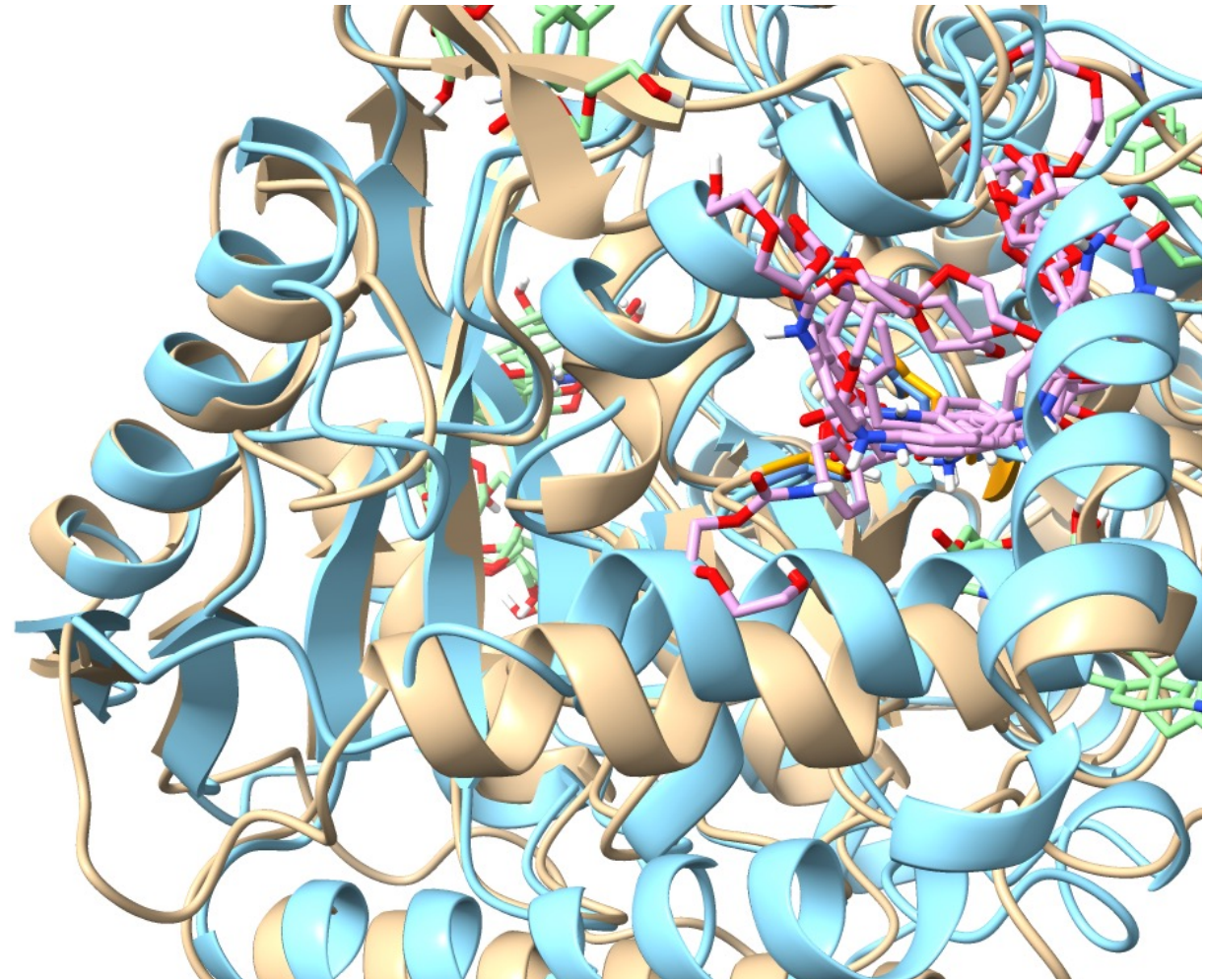




S. Anselmi *et al.*, *Green Chem.*, **2025**, 27, 12176

## PUases

- Enzyme mutagenesis
- Enzyme discovery
- Upcycling

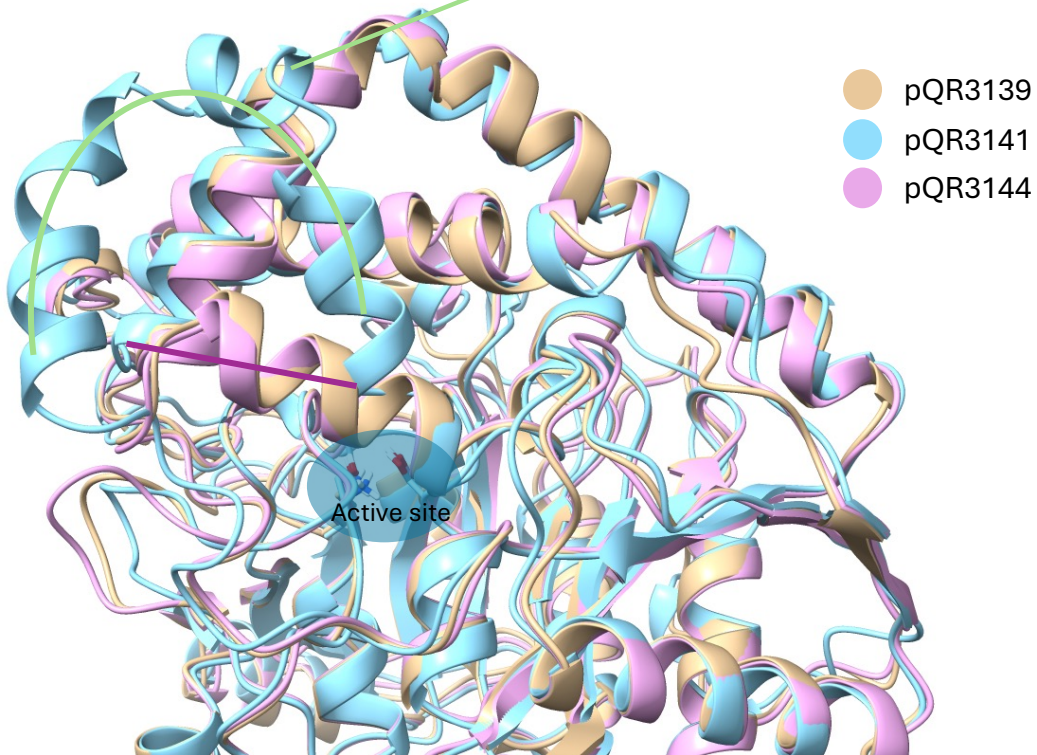




# Mutants design >>> Mutant library construction >>> Enzyme expression >>> Activity test

*How different are those enzymes?*

```
pQR3141 TVPALICEQDTPLWQQLALRPALPLGKILLKSGQVQKNA YNNLWRVPFTQLSNLSGTPSMSVP
pQR3139 HTTPRLGH-----LTPEQTFDEIM-----DKLRHYVSEFTPLNNANGTPAISLP
pQR3144 HSTPELGW-----LSPEQPFEELF-----ERLLRYVSEFTPLNNAAGSPAISLP
```



| Sequence pair | % Identity | % Positives |
|---------------|------------|-------------|
| 3139 vs 3141  | 37%        | 48%         |
| 3139 vs 3144  | 59%        | 71%         |
| 3141 vs 3144  | 36%        | 50%         |

- pQR3139 vs pQR3144 → relatively **high similarity**
- pQR3141 vs. pQR3139/pQR3144 → **more divergent**
- **The initial engineering on pQR3139 and pQR3141**

IPR036928 AS superfamily – 15,459 seq total

MFKNNDHA - Anaerobic digestion

EJDADBFL - Nylon bin bottom 1 nylon bottom bin 3 (NBB1NBB3)

JELBMCOI - Nylon bin top nylon bin bottom 2 (NBTNBB2)

FBMMANKB - Teabag compost

HFNIABNE - Envar leachate

KACGJKFO - Envar compost

EHPGCJKL - Belfast leachate

KAIEAEMD - Belfast compost

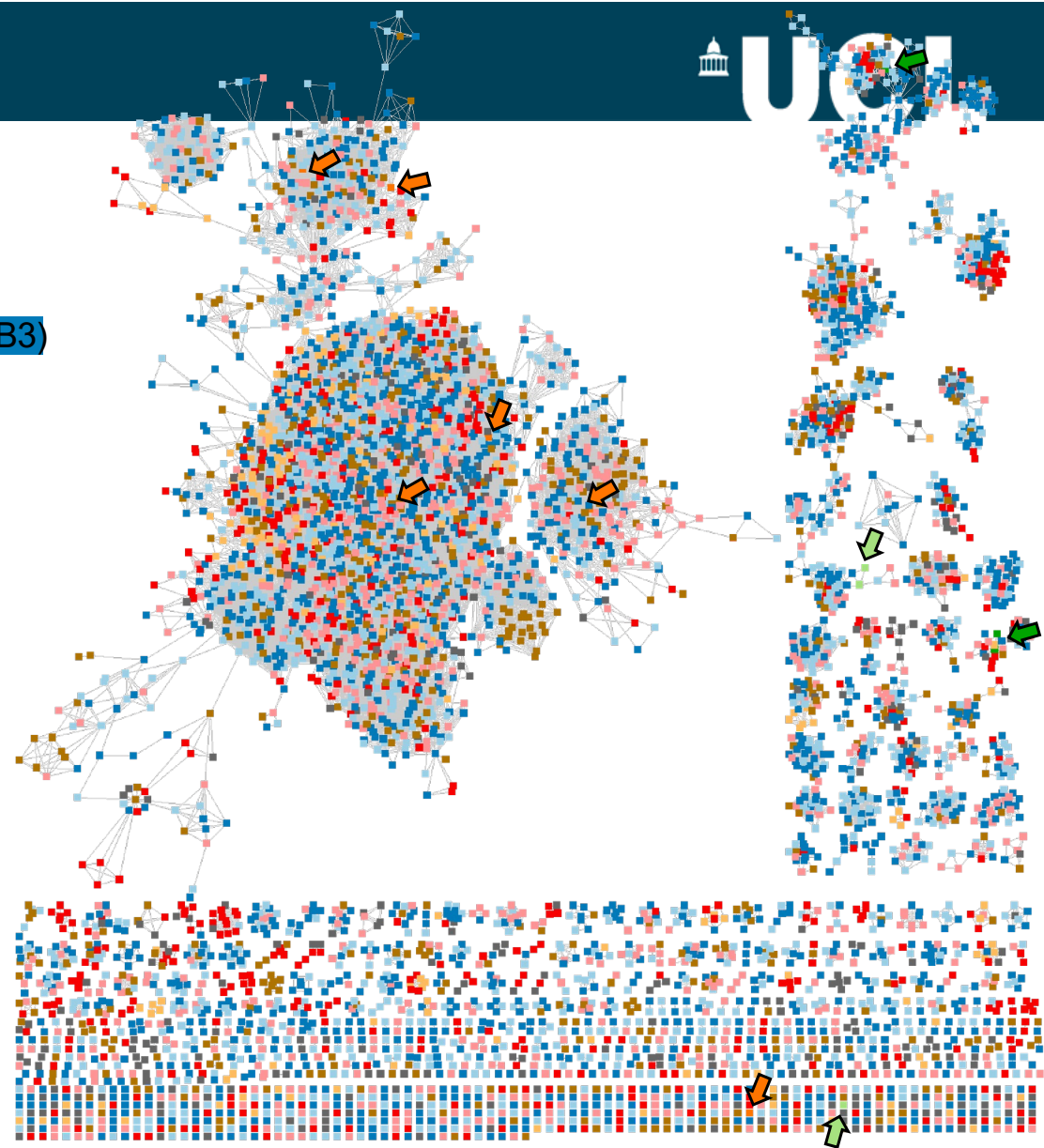
CNCAIEGK - Crocodile

Clustering at 55%

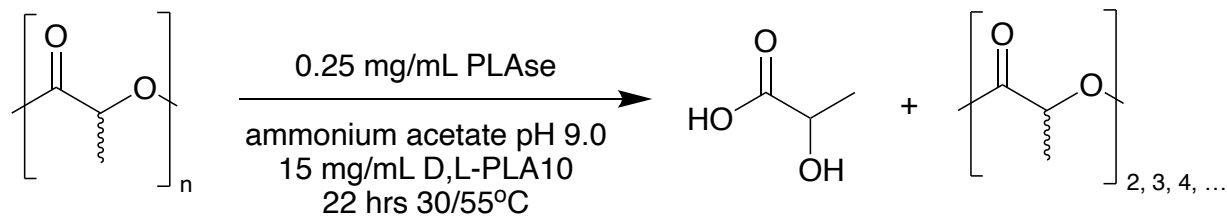
Literature UB

UCL working

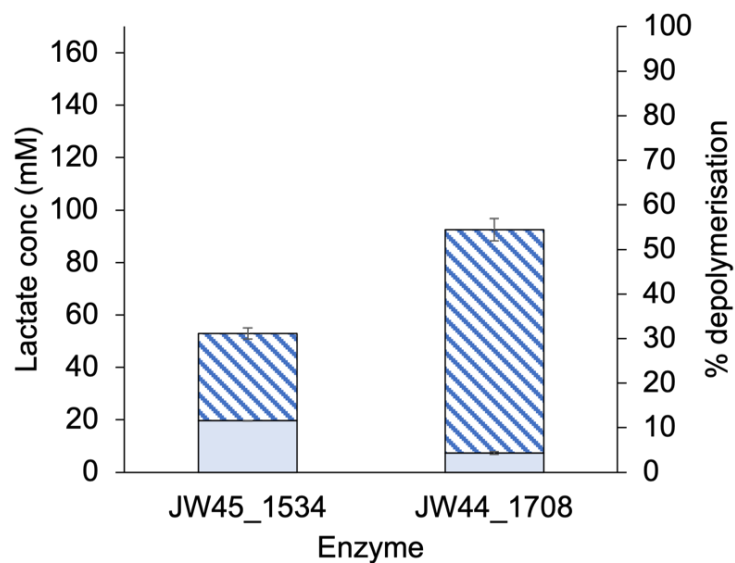
UCL not-working



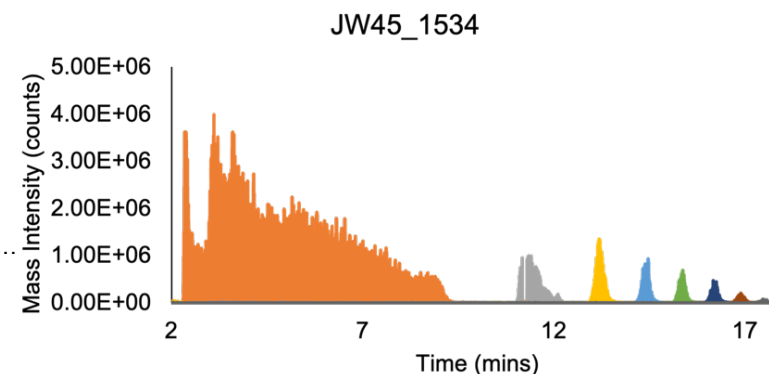
# Hotbin/IC enzymes - JW44\_1708 fully degrades solid PLA powder



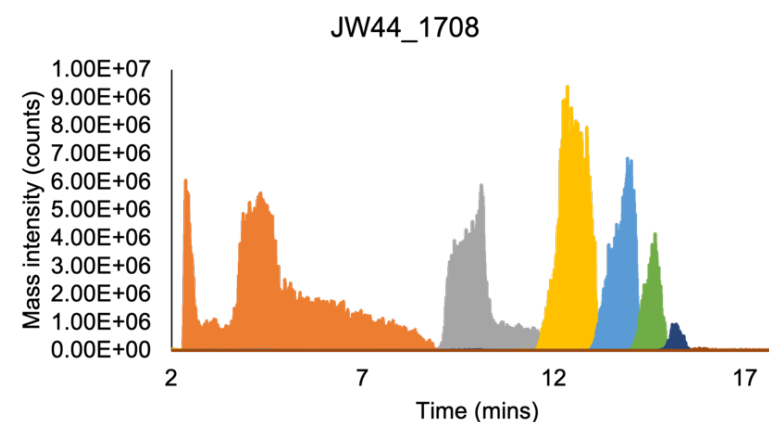
neg ctrl JW44\_1708



□ monomeric lactate    ▨ oligomeric lactate



— PLA2 — 3 — 4 — 5 — 6 — 7 — 8 — 9



— 2 — 3 — 4 — 5 — 6 — 7 — 8

# Acknowledgements



**Silvia Anselmi**  
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**Luba Prout**

***Jack Jeffries, Mark Miodownik, John Ward, PE3B Team***

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EPSRC, BBSRC, NERC, UCL Deans Prize



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# Microbial upcycling of non-conventional polyester feedstocks

**Dr Joanna Sadler**

Senior Lecturer in Biotechnology, University of Edinburgh

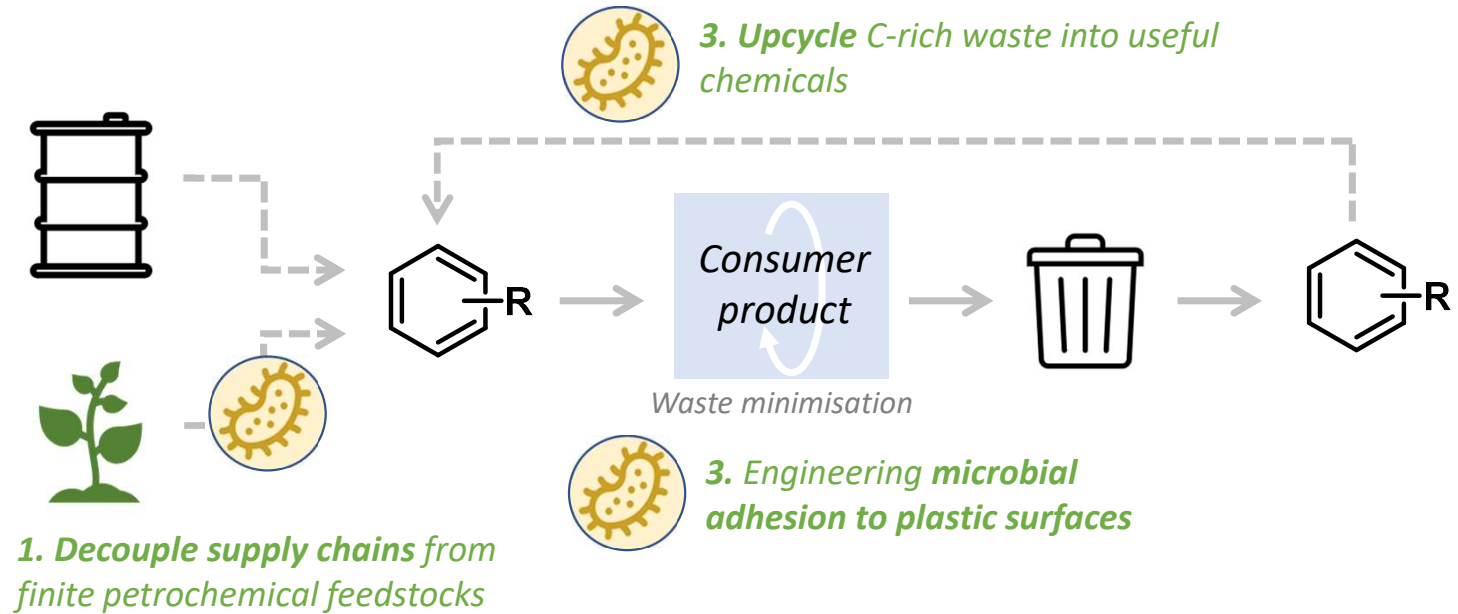
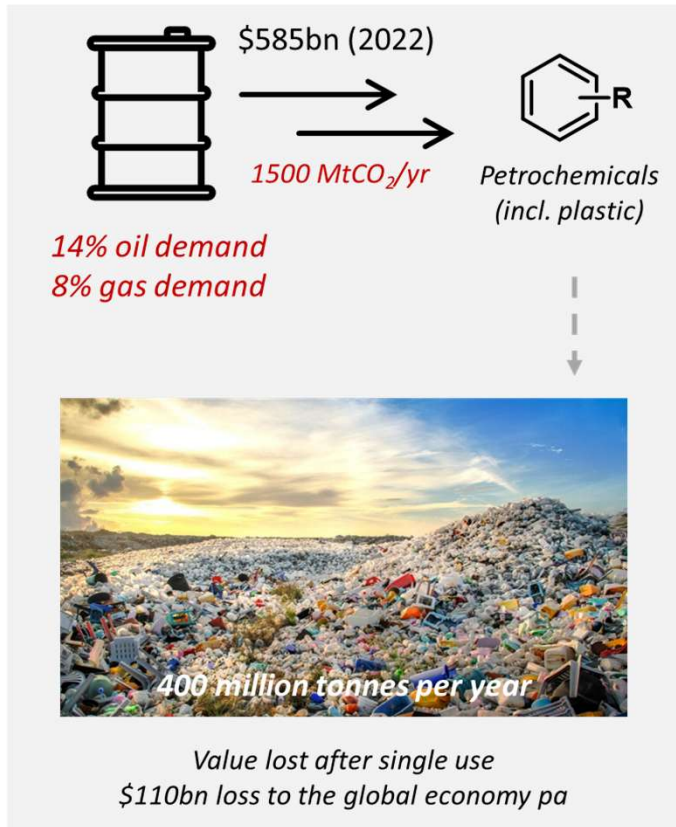
BBNet Conference, October 2025



[joanna.sadler@ed.ac.uk](mailto:joanna.sadler@ed.ac.uk)

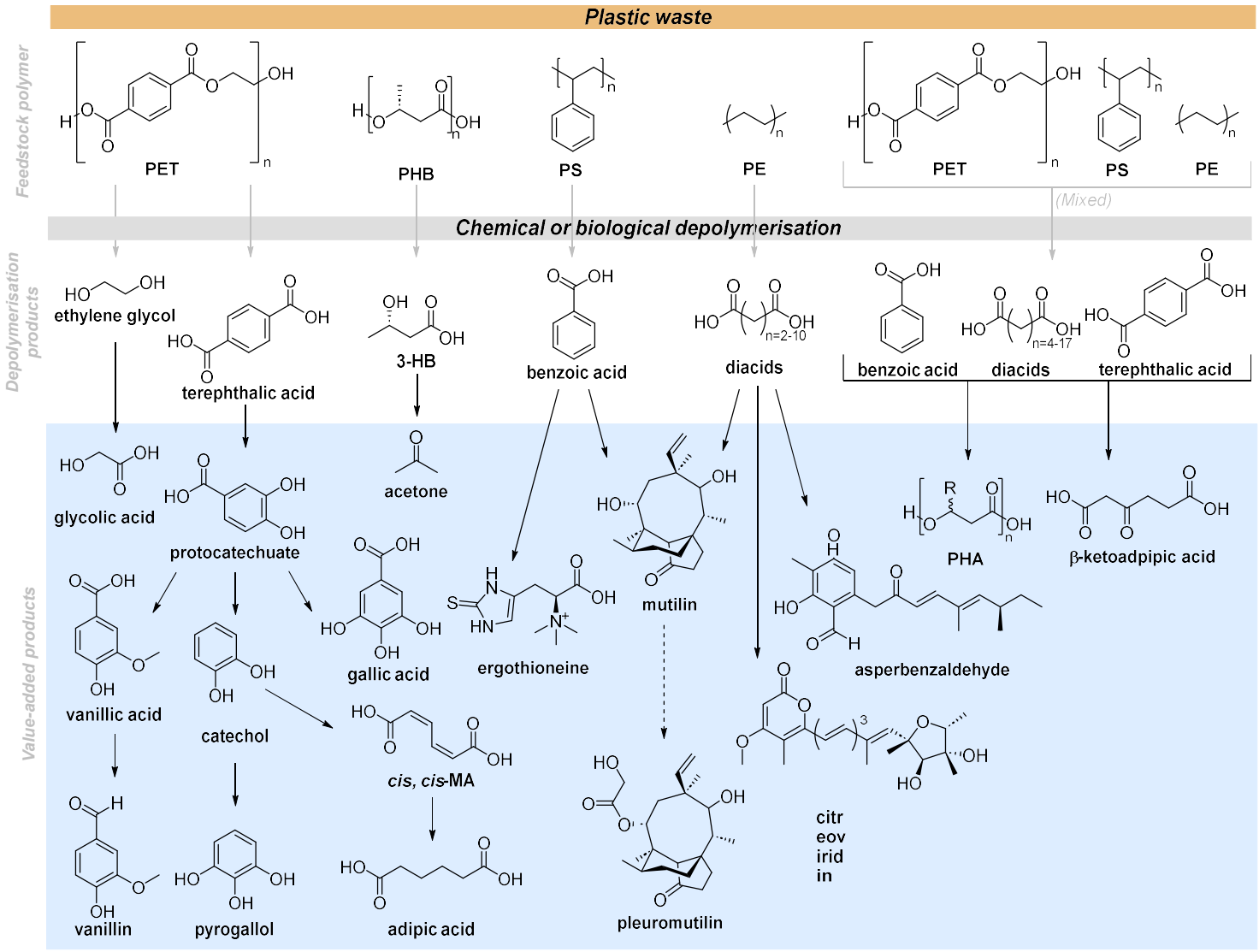
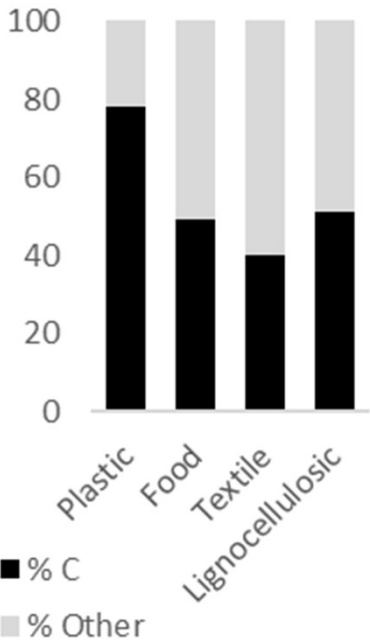
[www.sadlerlab.github.io](http://www.sadlerlab.github.io)

# Engineering Biology for a Sustainable Materials Future





# Plastic Bio-upcycling: a promising field

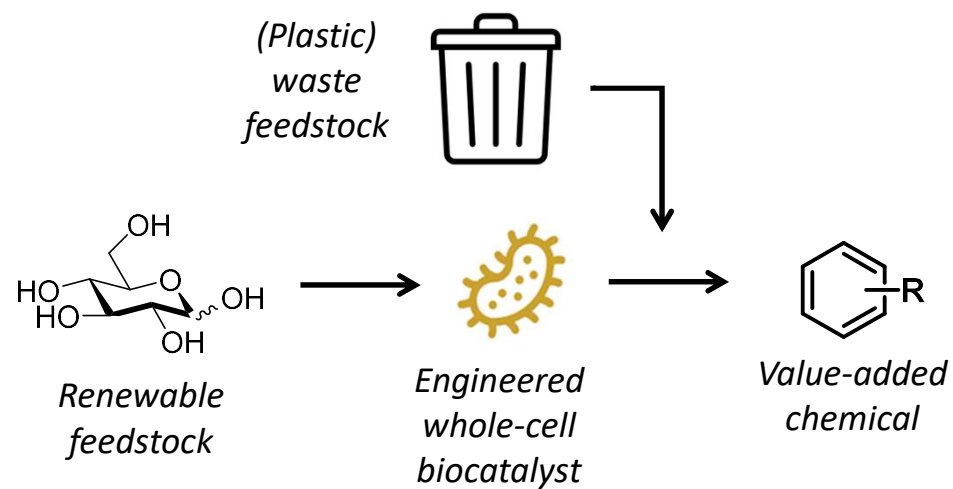
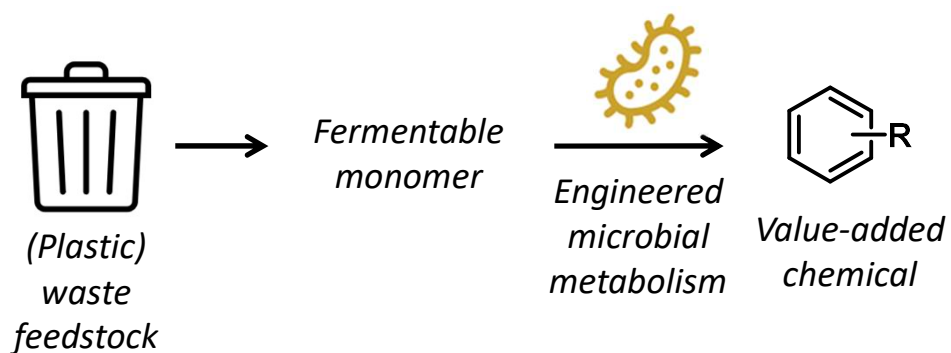


## Plastic Bio-upcycling: a promising field

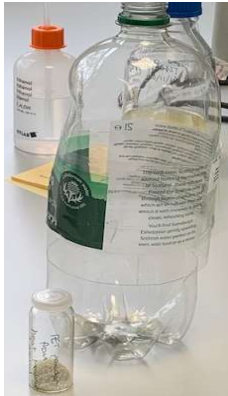
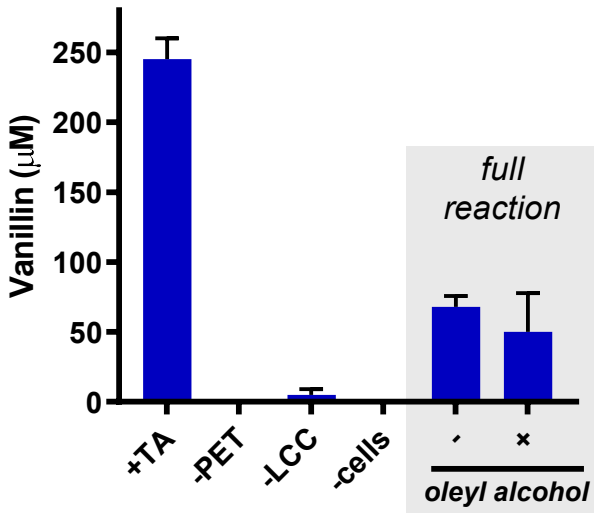
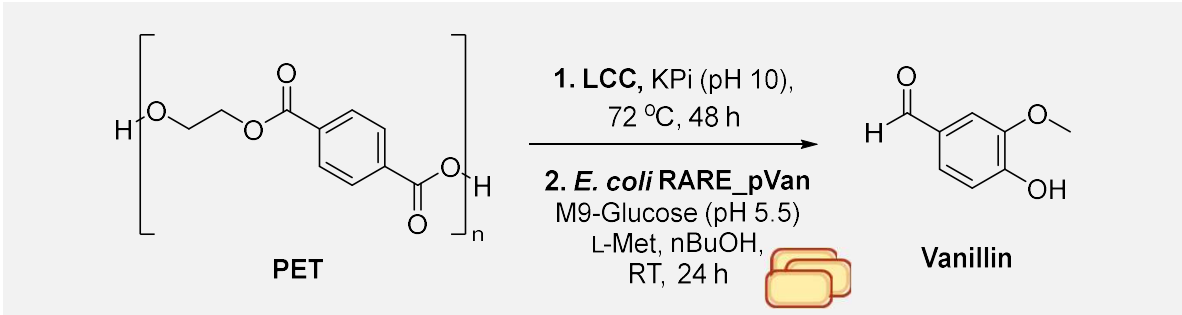
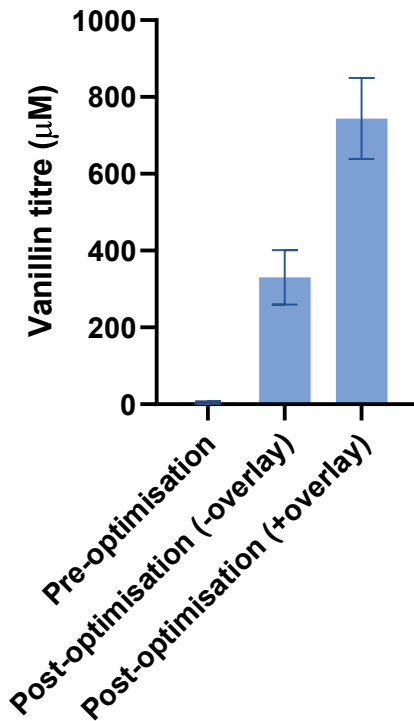
### Direct fermentation

VS

### Whole cell biocatalysis



# Plastic bottles – a starting point





## *Real-world feedstocks are complex*



*Complex, heterogeneous composition*

*Additives: stabilisers, dyes, co-polymers*

*Contaminants from use*

*Microbes are experts at adapting to stress and reaction selectivity*

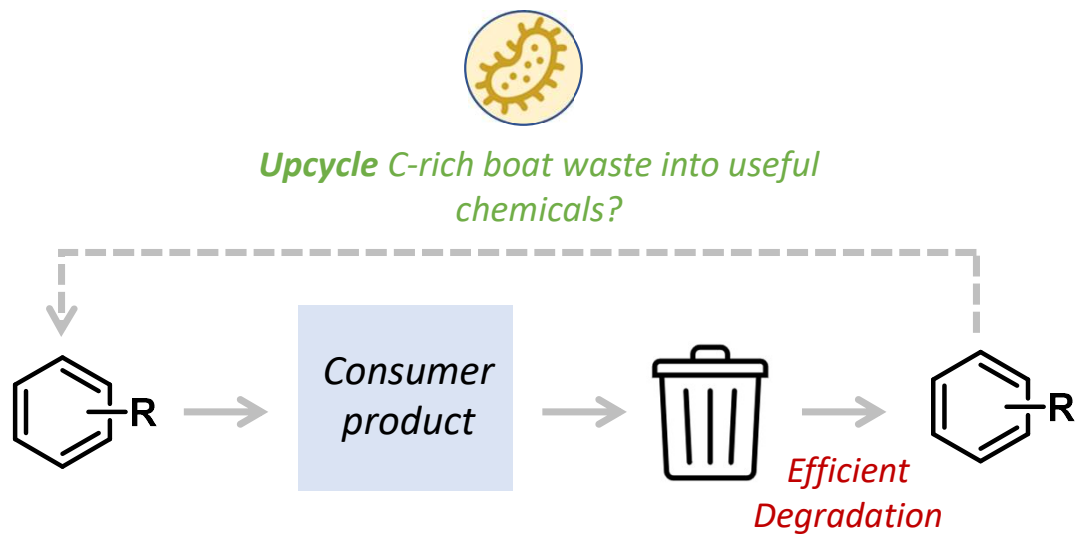
*Direct engagement with industry: direct route to impact*

# Bio-upcycling.. Boats?!

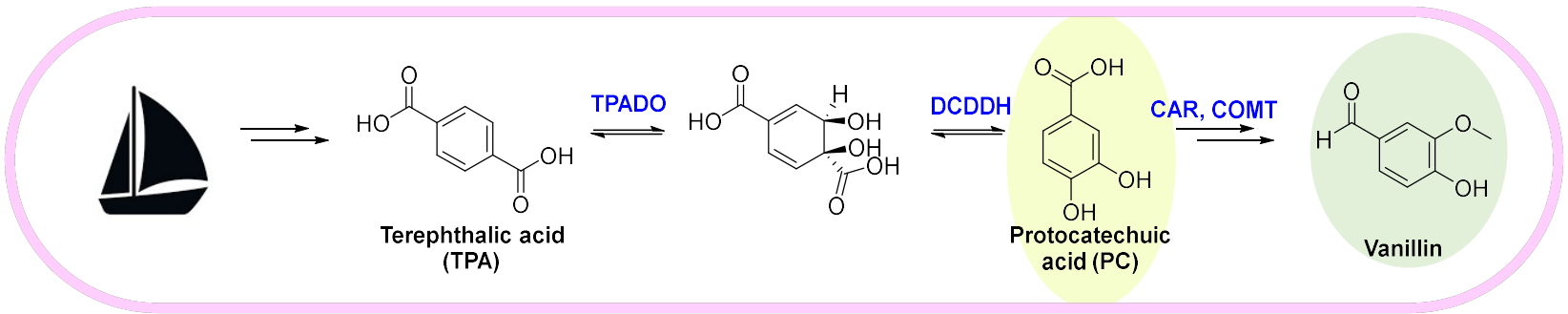
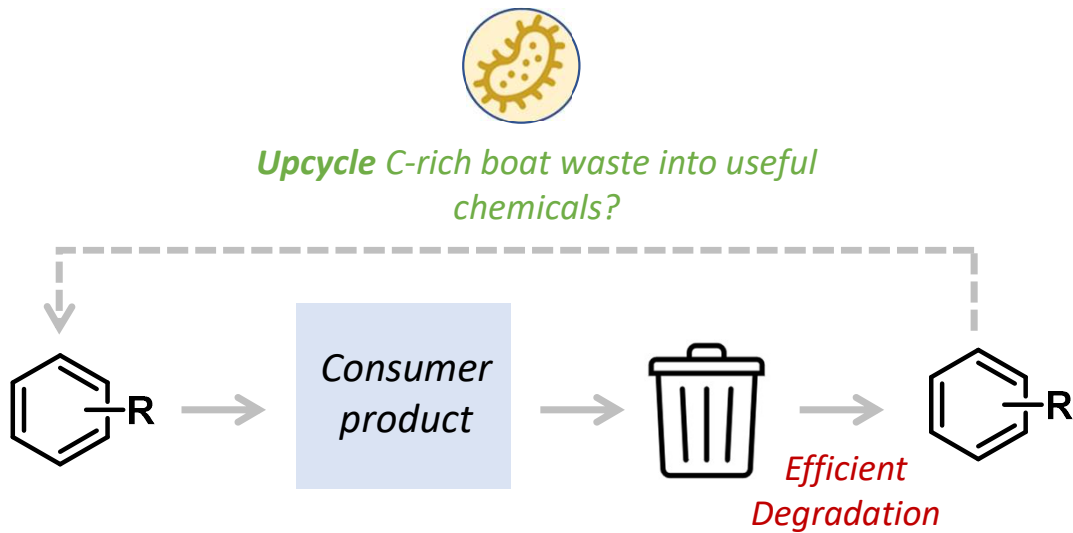


*Sails: 80-90% PET  
~2500 tonnes waste annually*

*Glass fibre composites: up to 90% waste  
1.4Bn kg waste annually*



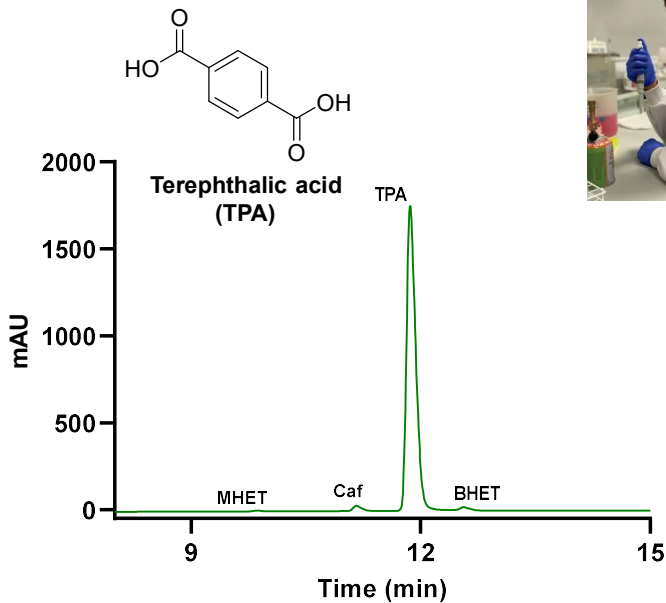
# Bio-upcycling.. Boats?!



# Bio-upcycling.. Boats?!



DeeCom  
→



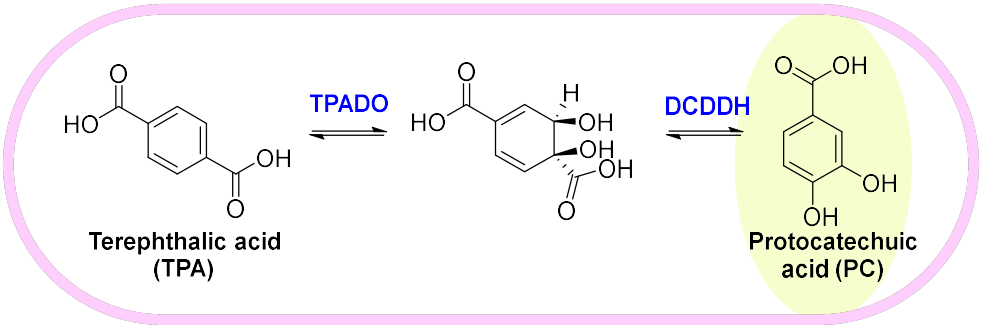
Process to concentrate TPA to up to ~900 mM from 'sail hydrolysate'

Very clean profile by HPLC – contaminants below LoD

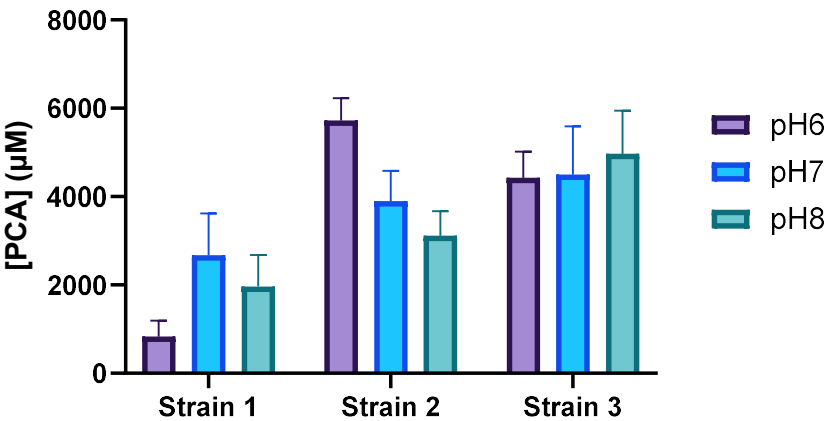
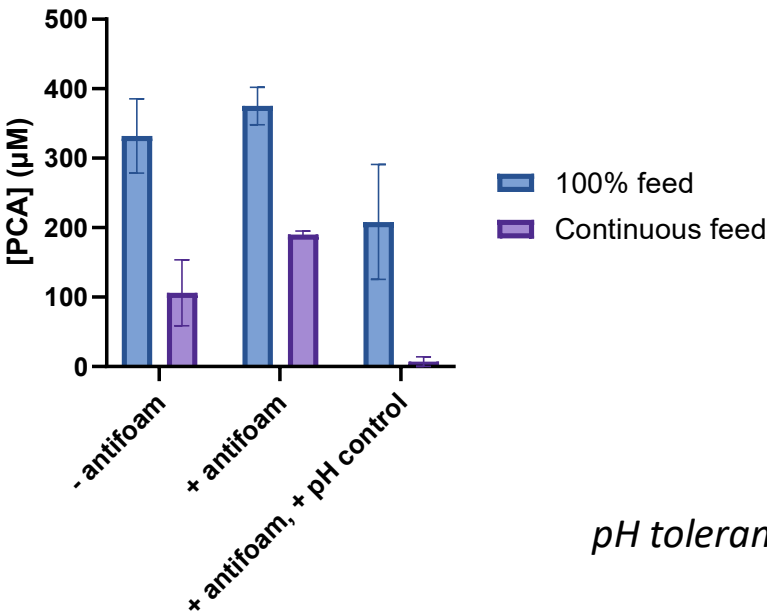
Added to bioprocess as disodium salt



# Bio-upcycling.. Boats?!



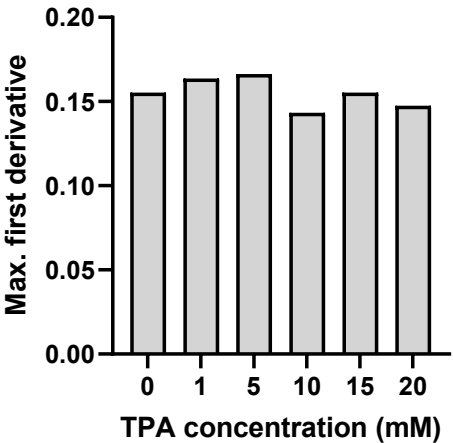
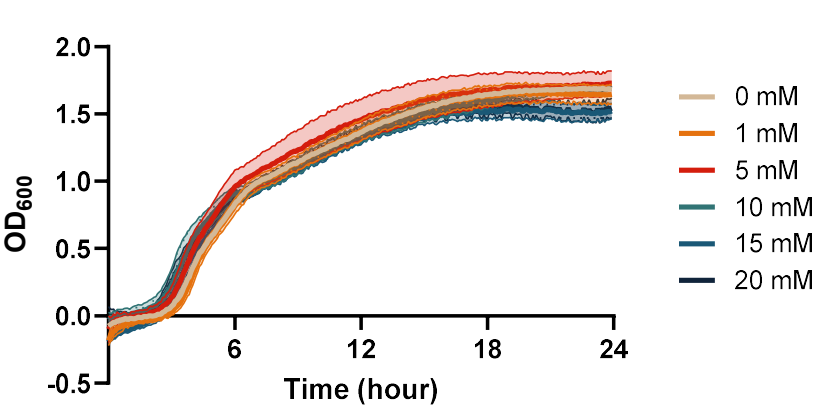
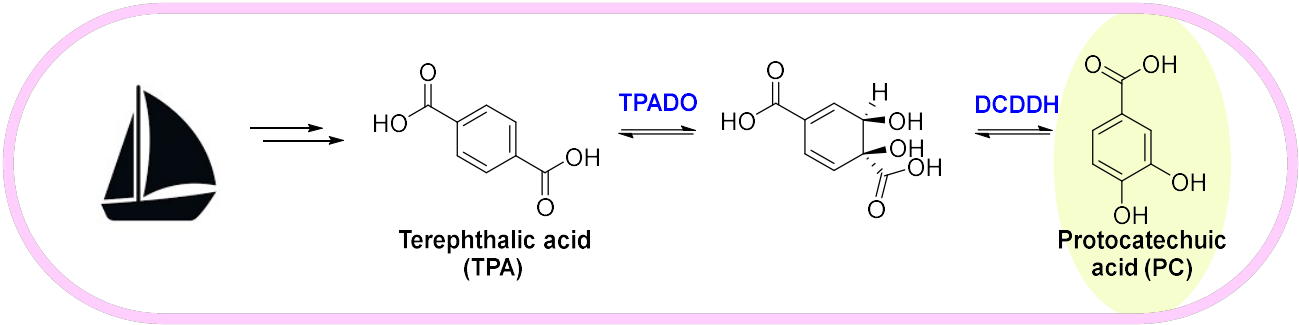
Edinburgh  
Genome  
Foundry



*pH tolerance is strain dependent*

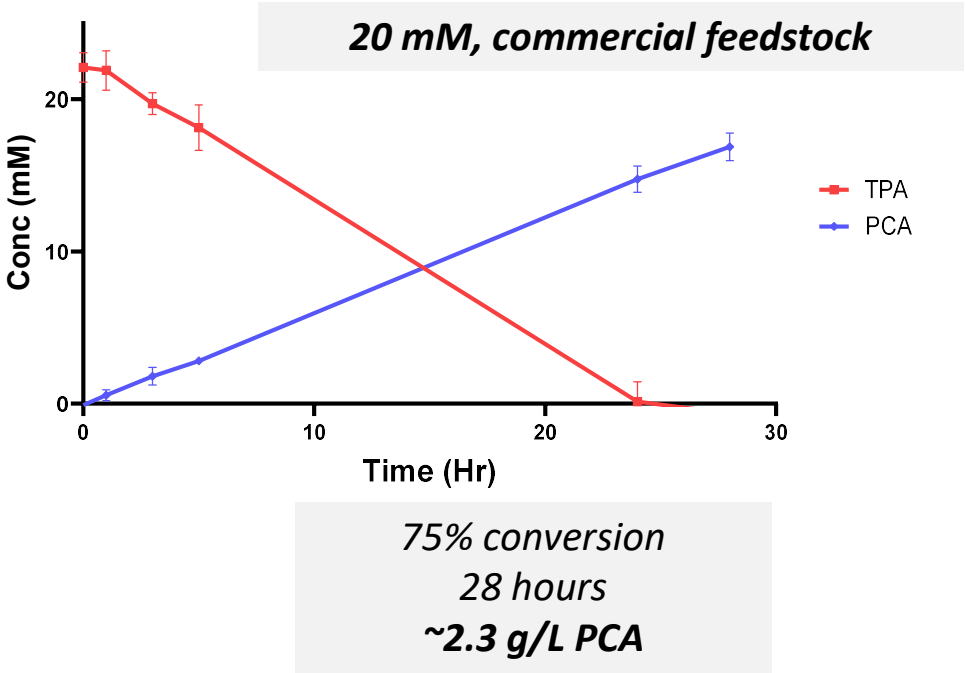
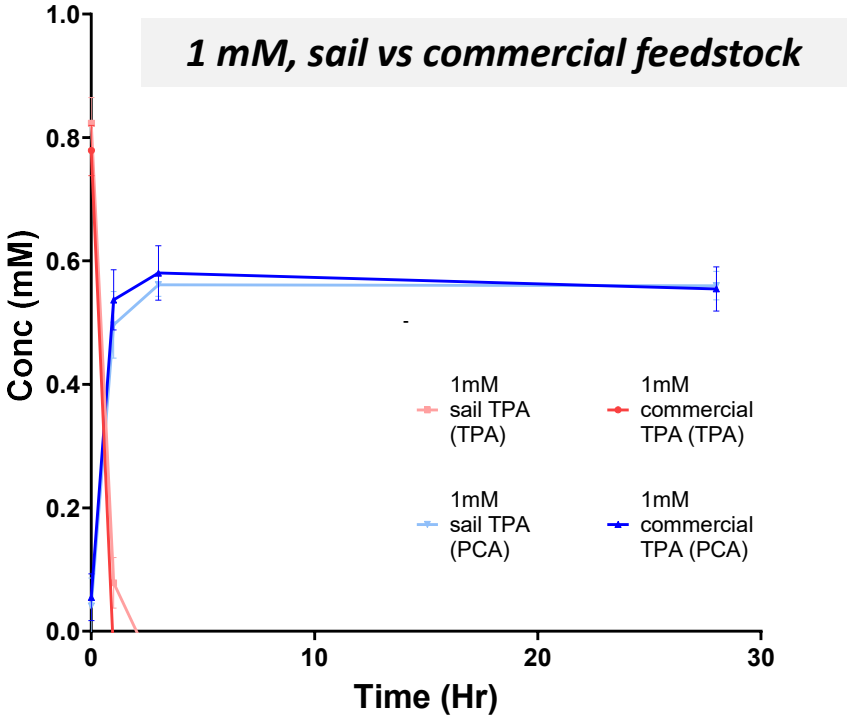
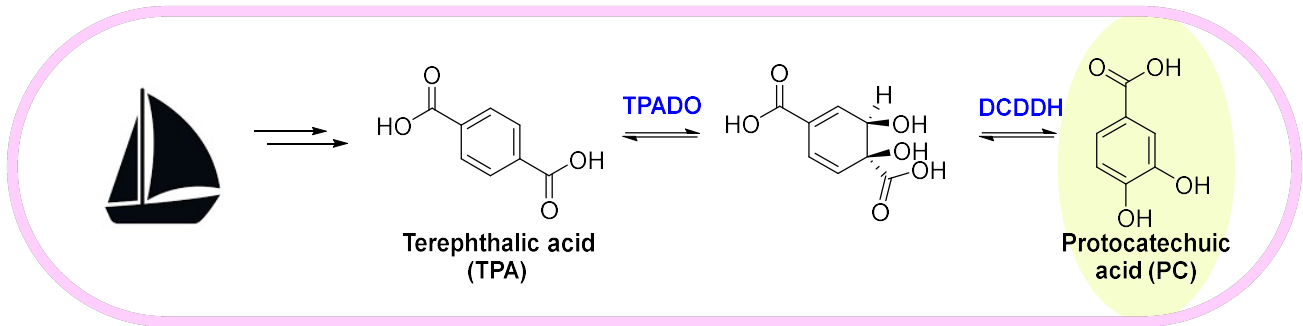
*6 mM PCA at BioLector scale from commercial TPA*

# Bio-upcycling.. Boats?!

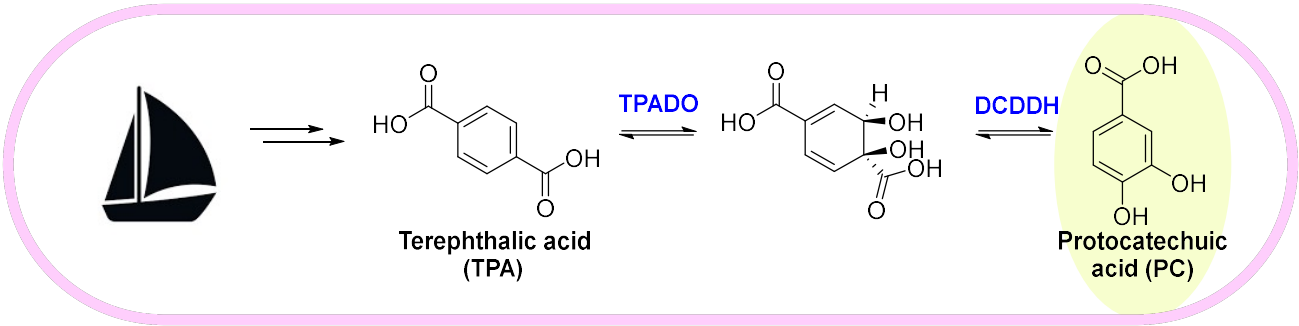


*E. coli* can tolerate sail-TPA at assay relevant concentrations

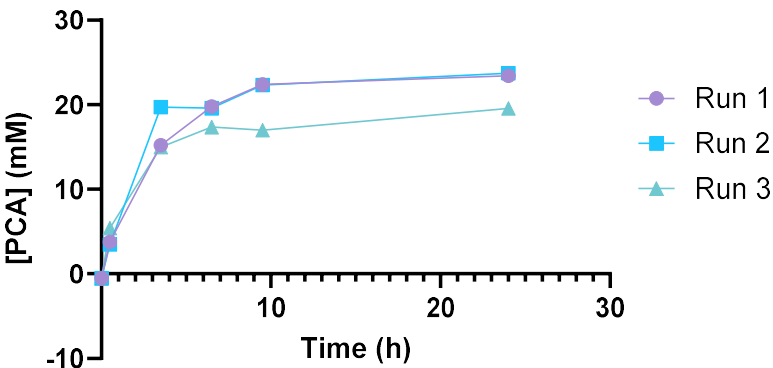
# Bio-upcycling.. Boats?!



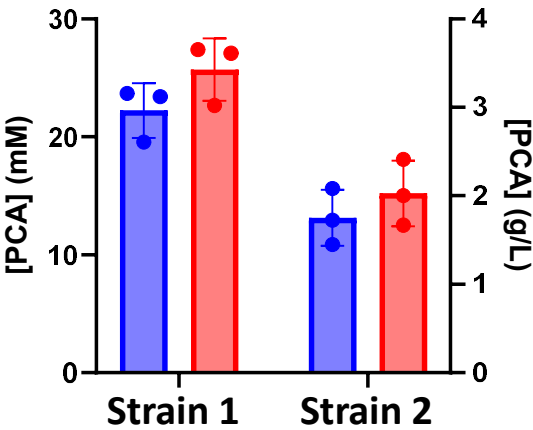
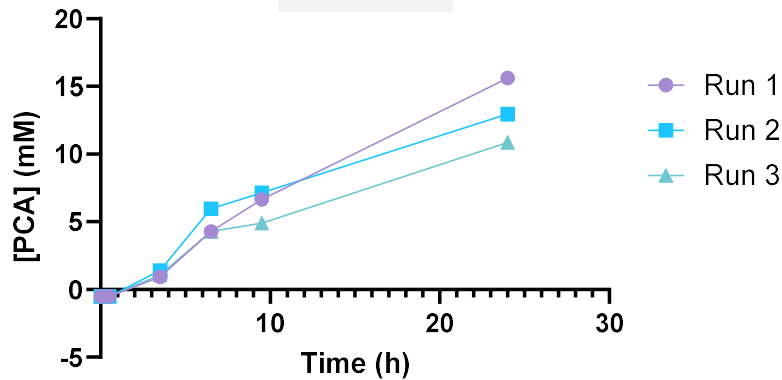
# Bio-upcycling.. Boats?!



Strain 1



Strain 2



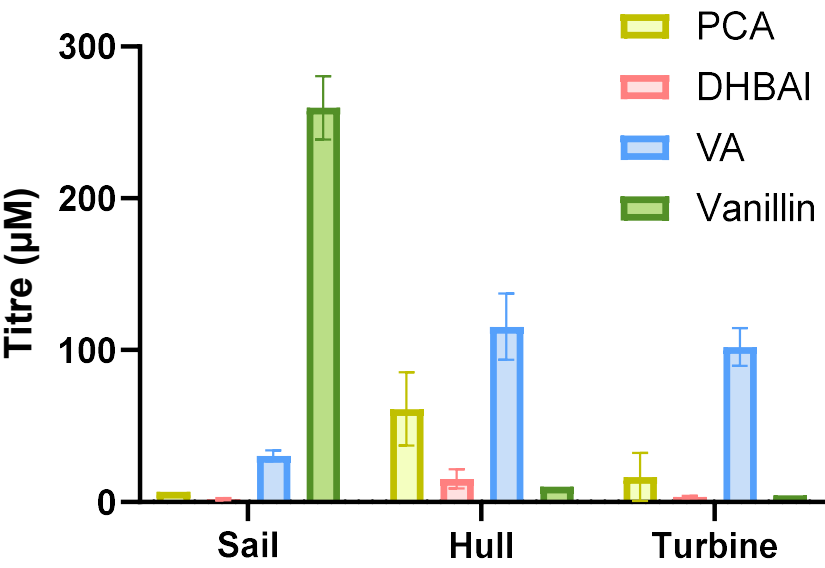
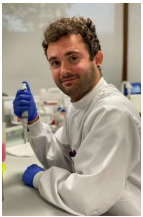
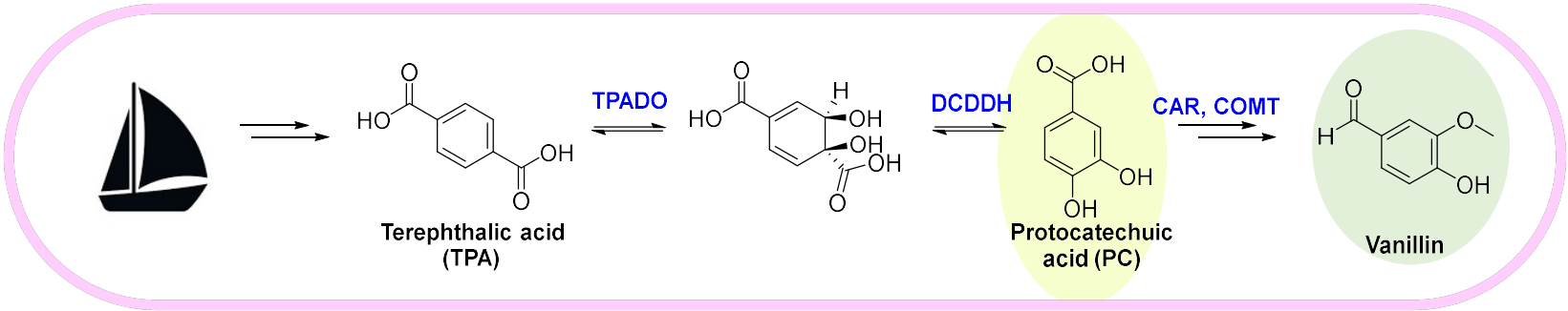
1 L Bioreactor scale, 'in situ whole cell biocatalysis' process

~3.5 g/L PCA from sail-TPA

● [PCA] (mM)  
 ● [PCA] (g/L)



# Vanillin from boat waste

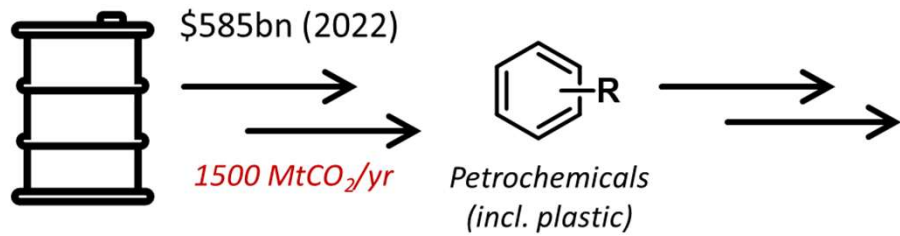


*PoC for upcycling of complex composite feedstocks*

*Hybrid process*

*Sails most imminently scalable; further engineering for fibreglass composites*

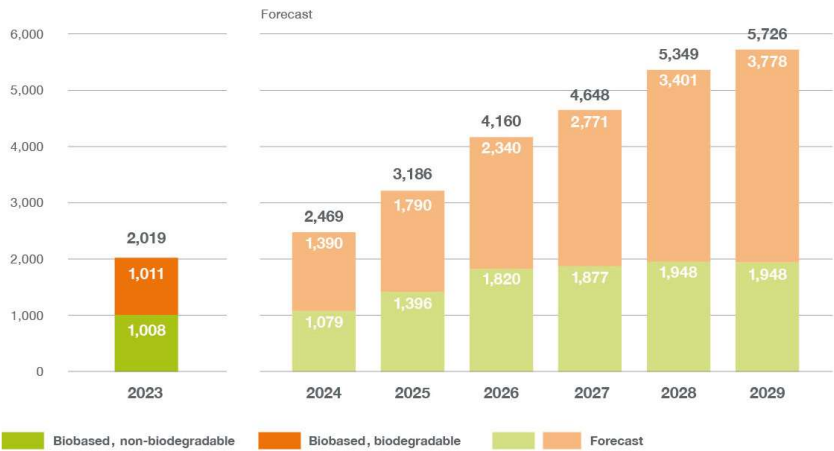
# Plastics: an inflection point?



Value lost after single use  
\$110bn loss to the global economy pa

## Global production capacities of bioplastics

in 1,000 tonnes



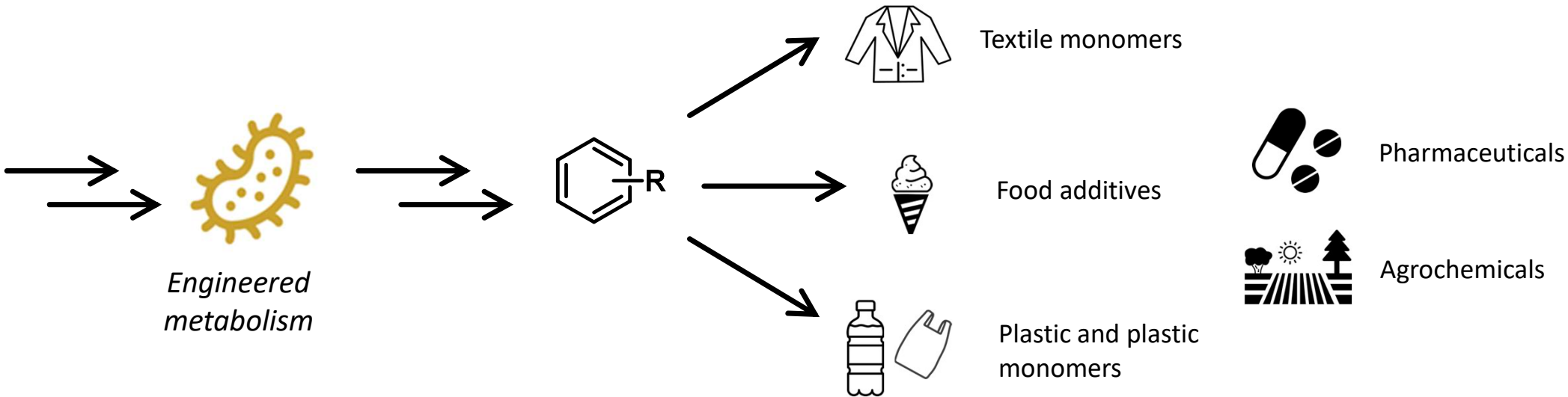
Source: European Bioplastics, nova-Institute (2024)



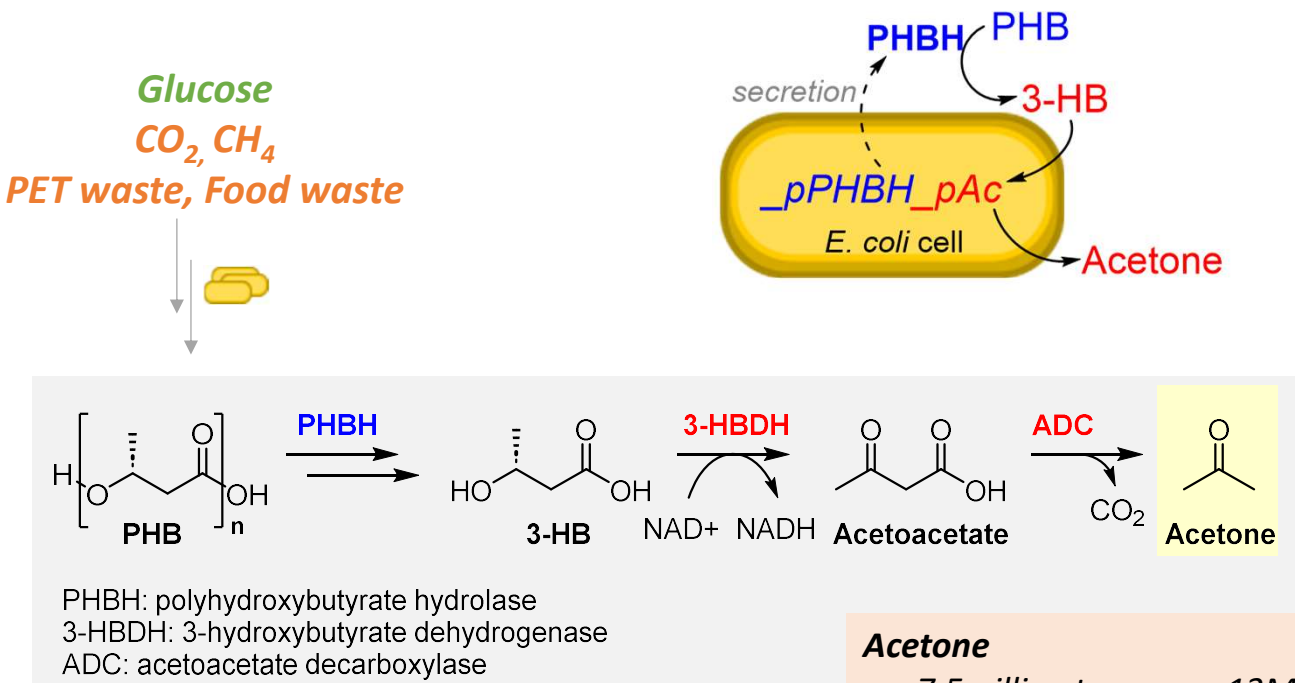
## ***Beyond 'biodegradable'***



# Beyond 'biodegradable'

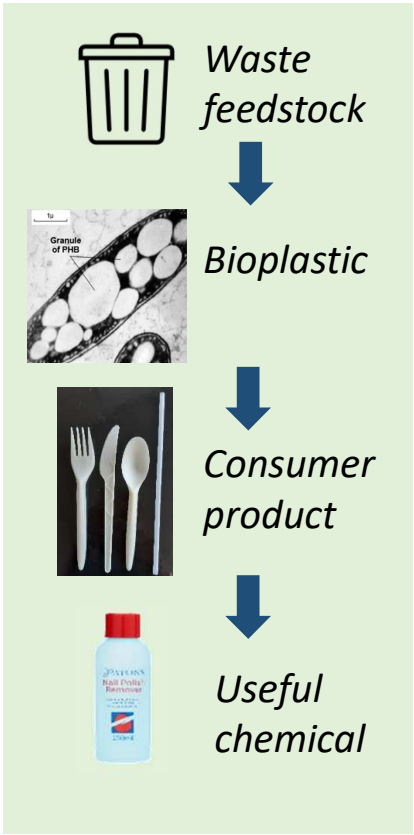


# Beyond 'biodegradable'



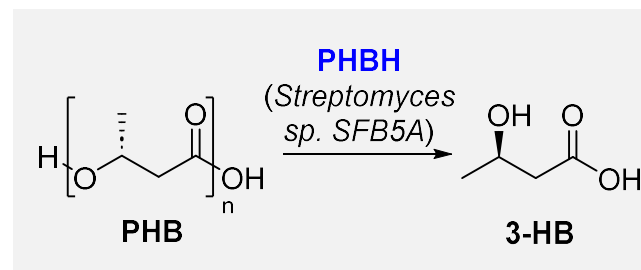
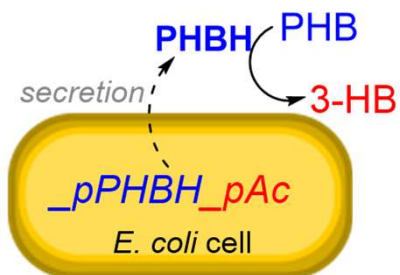
**Acetone**

- 7.5million tonne pa, 13M by 2030
- Currently petrochemical derived (cumene process)
- 2.55 kgCO<sub>2</sub>e/kg acetone

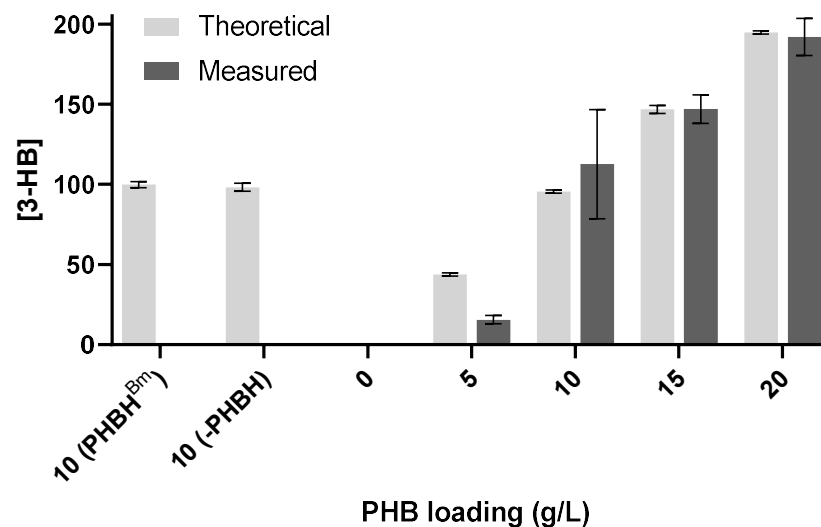




# Beyond 'biodegradable'

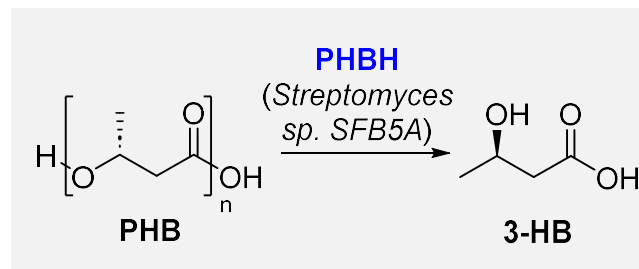
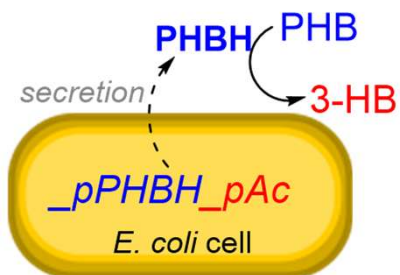


| Time (hrs)                                          | 0 | 2 | 4 | 22 |
|-----------------------------------------------------|---|---|---|----|
| BL21_EpET extracellular fraction (37 °C incubation) |   |   |   |    |
| BL21_pSTR extracellular fraction (37 °C incubation) |   |   |   |    |
| BL21_pSTR extracellular fraction (30 °C)            |   |   |   |    |

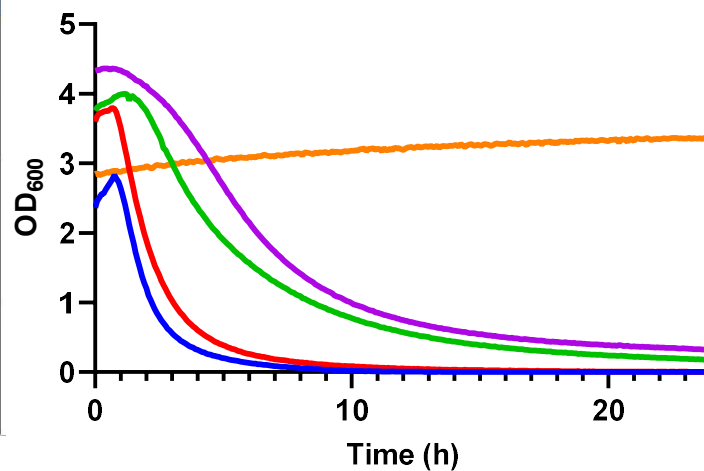


***PHB is rapidly degraded by secreted PHBase***

# Beyond 'biodegradable'

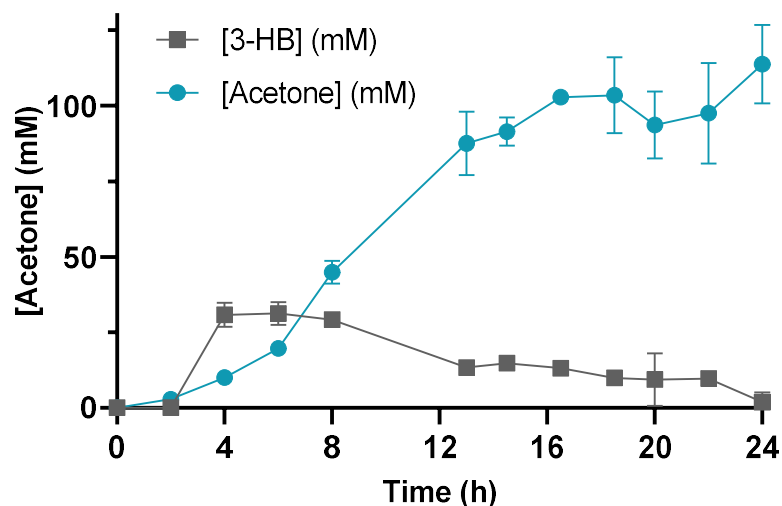
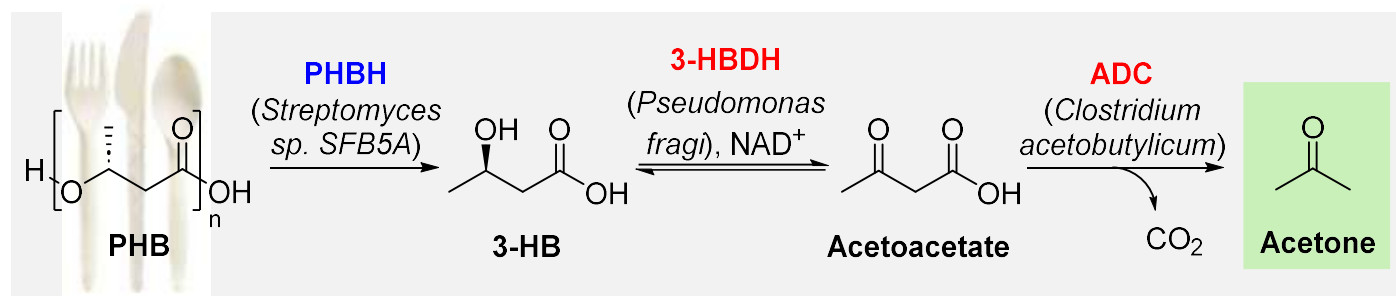
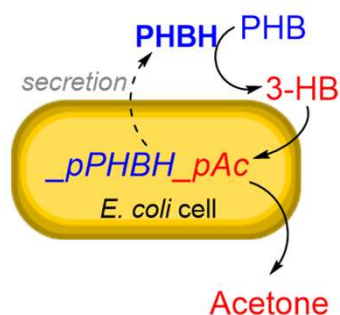


| Time (hrs)                                          | 0 | 2 | 4 | 22 |
|-----------------------------------------------------|---|---|---|----|
| BL21_EpET extracellular fraction (37 °C incubation) |   |   |   |    |
| BL21_pSTR extracellular fraction (37 °C incubation) |   |   |   |    |
| BL21_pSTR extracellular fraction (30 °C)            |   |   |   |    |

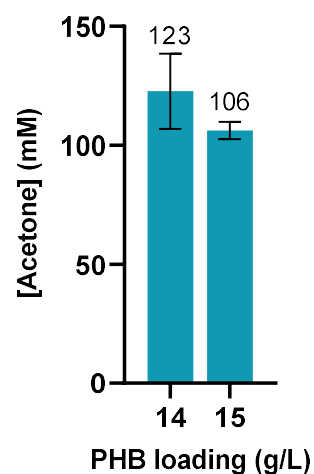


**PHB is rapidly degraded by secreted PHBase**

# Beyond 'biodegradable': Acetone from PHB



100% conversion in 24 hours (11 g/L)

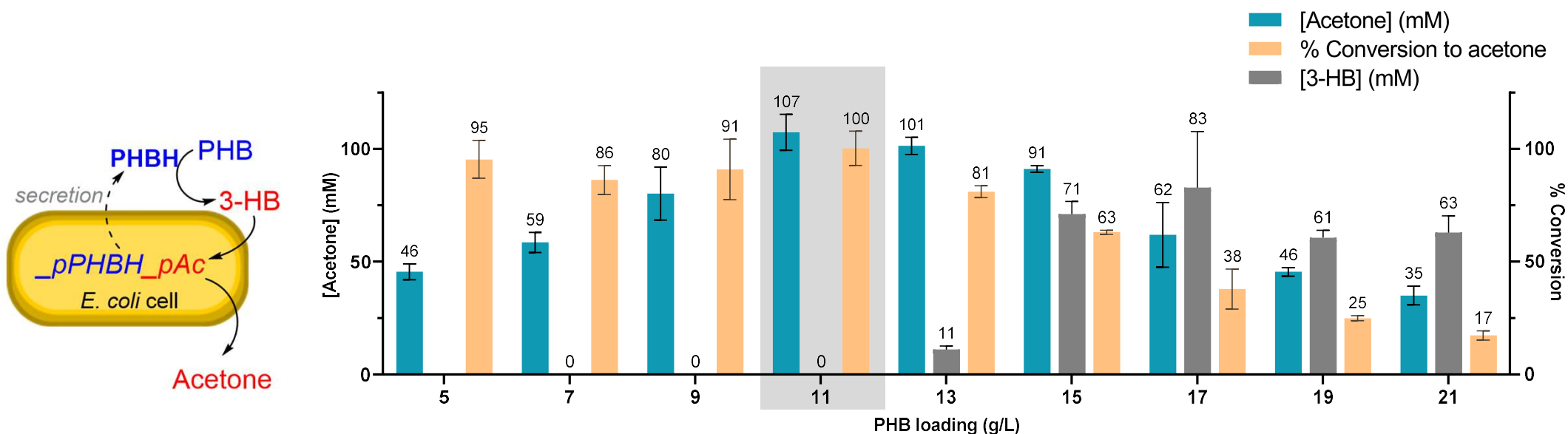


123 mM  
~7 g/L acetone

**One-step, single strain PHB to acetone production process in water at 30 °C**

**Biodegradable waste: an ideal feedstock for the circular bioeconomy**

# Beyond 'biodegradable': Acetone from PHB

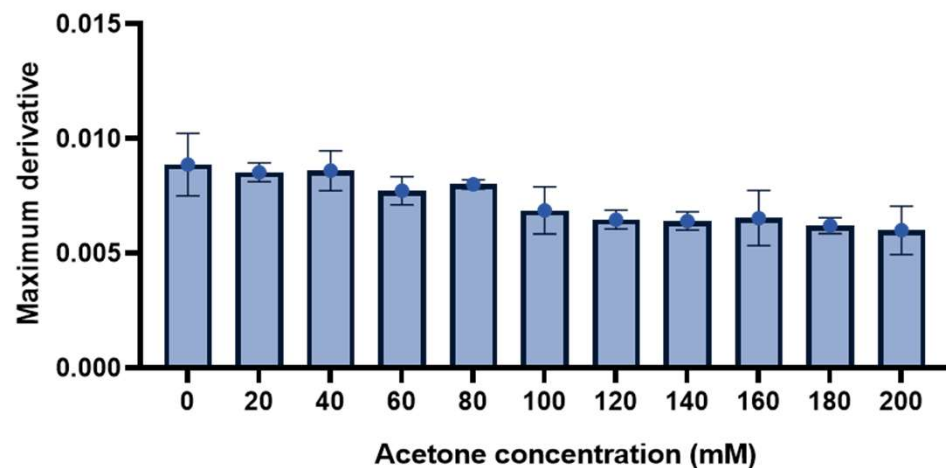


*Rate PHB degradation > rate 3-HB to acetone production*

*Above 11 g/L, 3-HB hypothesised to accumulate and have toxic effect on cells, slowing acetone production*

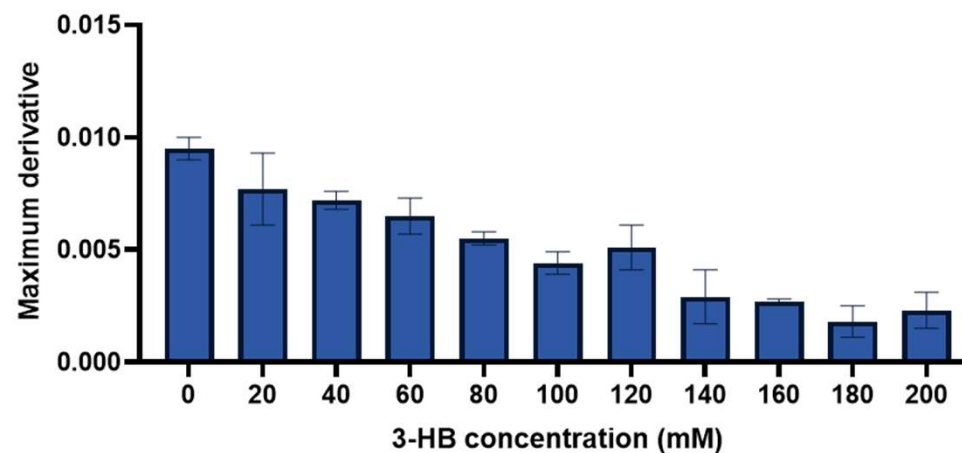
## 3-HB is surprisingly toxic!

*\_pPHBH\_pAc + Acetone*



*Acetone is well-tolerated*

*\_pPHBH\_pAc + 3-HB*

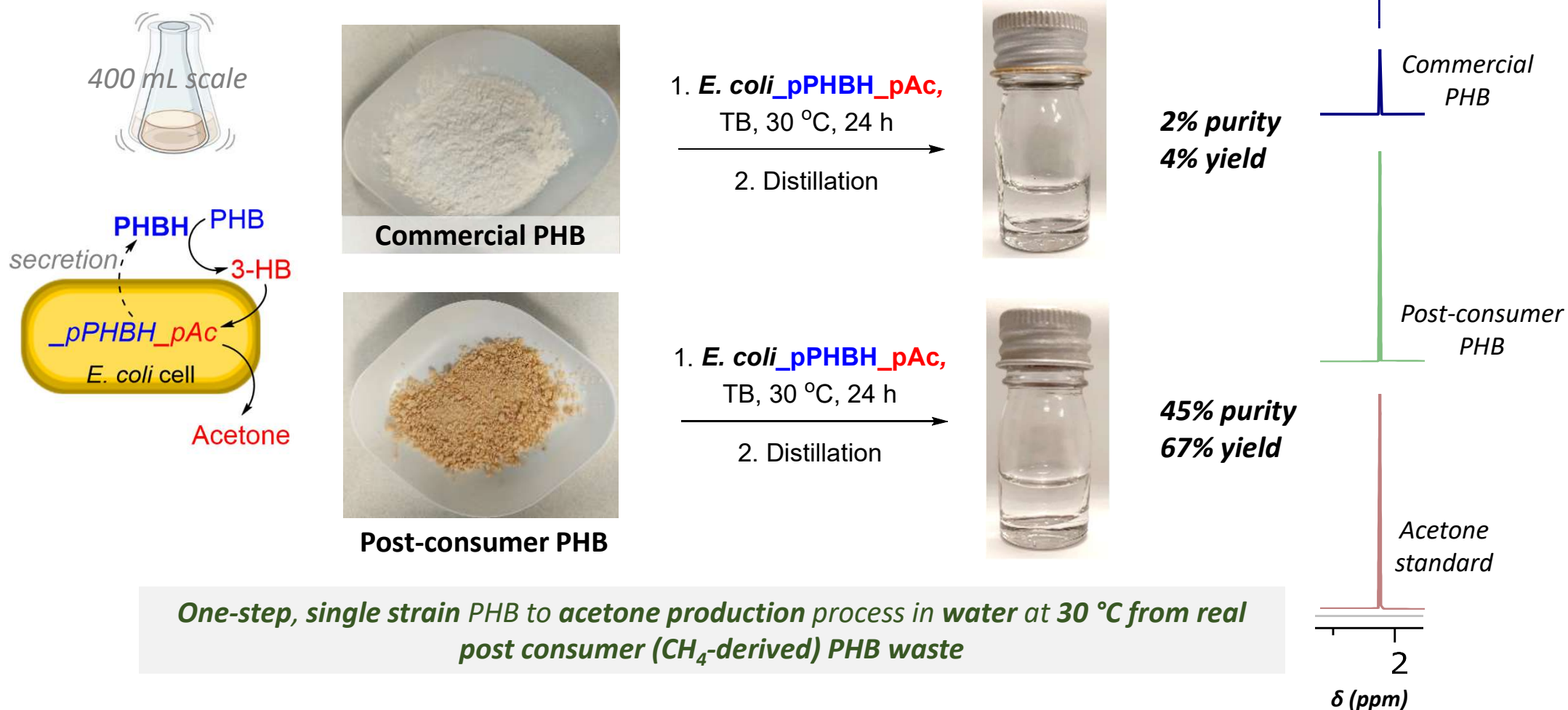


*3-HB inhibits growth rate >40 mM*

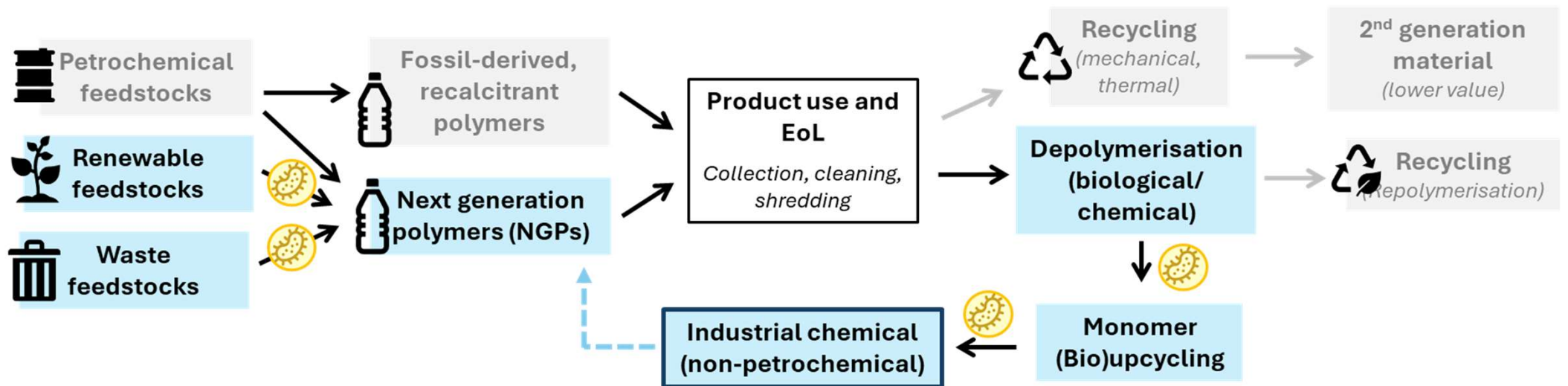
*(NB: 3-HB sodium salt used for experiments)*



# Beyond 'biodegradable': Acetone from PHB



# Outlook



**The Sadler Lab**  
Dr Médoune Sarr  
Dr Liz Lau  
Pedro Rangel de Faria  
Benjamin Armijo Galdames  
Franca Pitzalis  
Arianna Schneier  
Suhasini Iyer  
Matthew Whitehead  
Will Green



**Past lab members**

Dr Matt Edmundson  
Dr Michael McDonald

**Sustainable Extricko**

Dr Joe Penhaul Smith

**IBiolC: FlexBio**



[joanna.sadler@ed.ac.uk](mailto:joanna.sadler@ed.ac.uk)  
<http://sadlerlab.github.io>

THE  
**ROYAL  
SOCIETY**



Biotechnology and  
Biological Sciences  
Research Council



Engineering and  
Physical Sciences  
Research Council



THE UNIVERSITY of EDINBURGH  
School of Biological Sciences

Innovate  
UK





# Fueling a greener future with waste

**Jack Chengzhi Guo**

*jcguo@protonera.com*





# 420M

tons of plastics produced every year

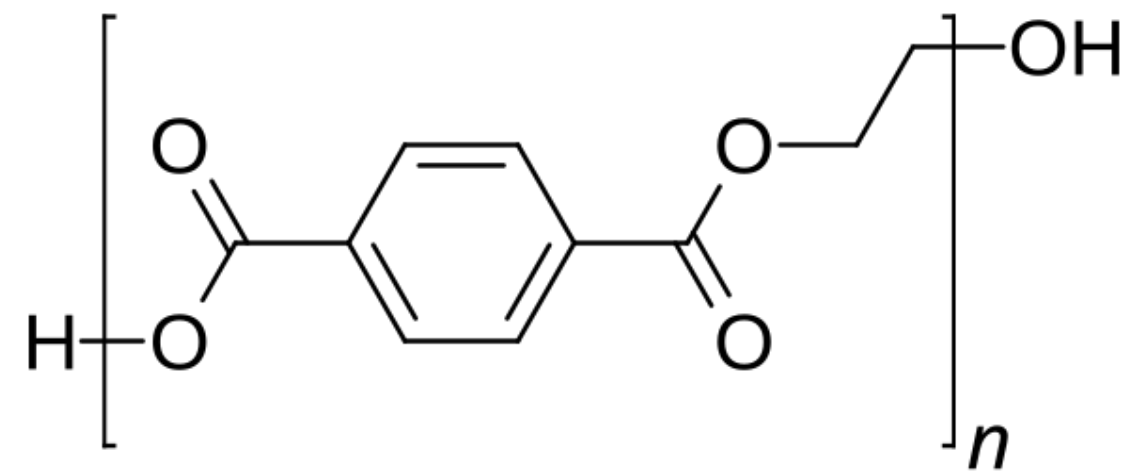
# 9%

of plastics ever produced

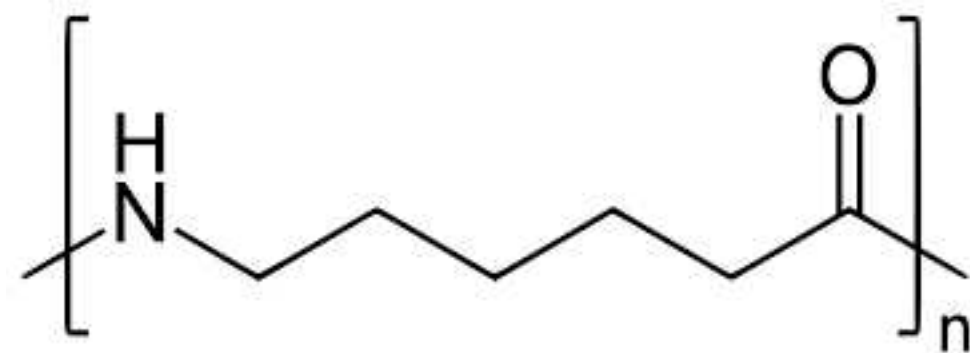




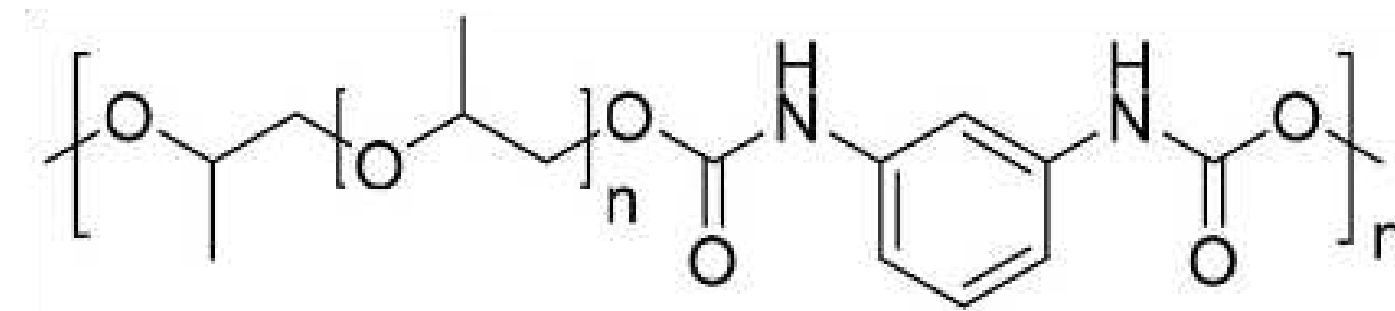
## Chemical Potentials Untapped



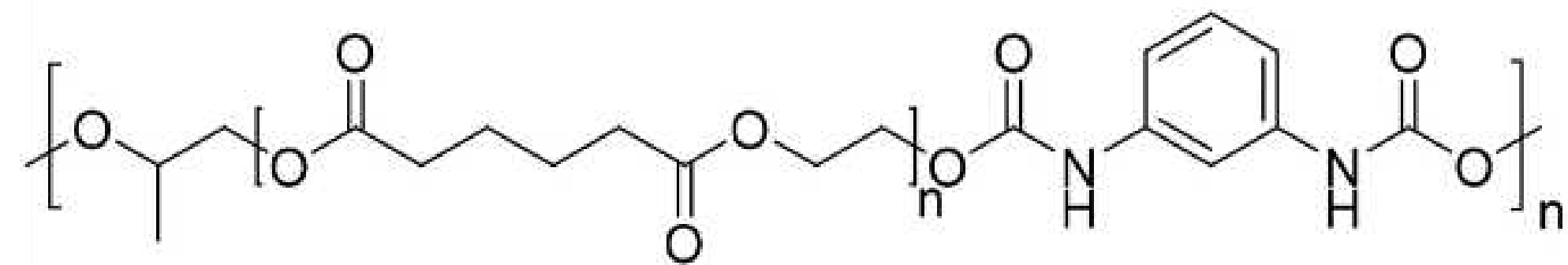
Polyethelene Terephthalate



Polyamide 6



Polyether polyurethane

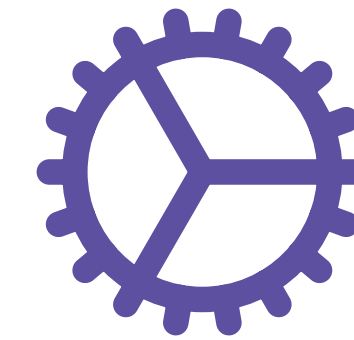


Polyester polyurethane

## Making resource efficiency/biorefining viable



Feedstock availability



Cost and efficiency

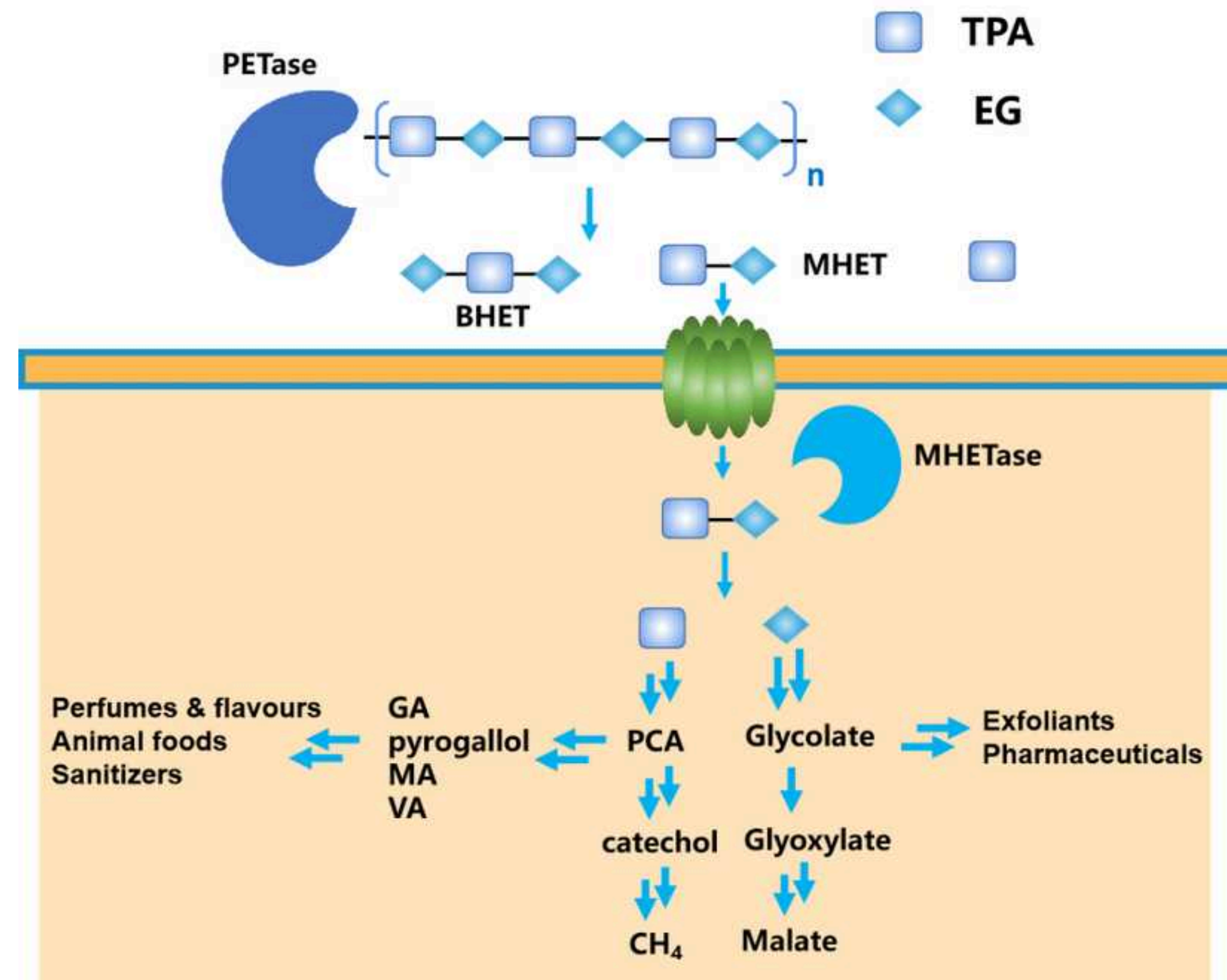


Product purity



Product market fit

# Depolymerisation is crucial for plastic valorisation

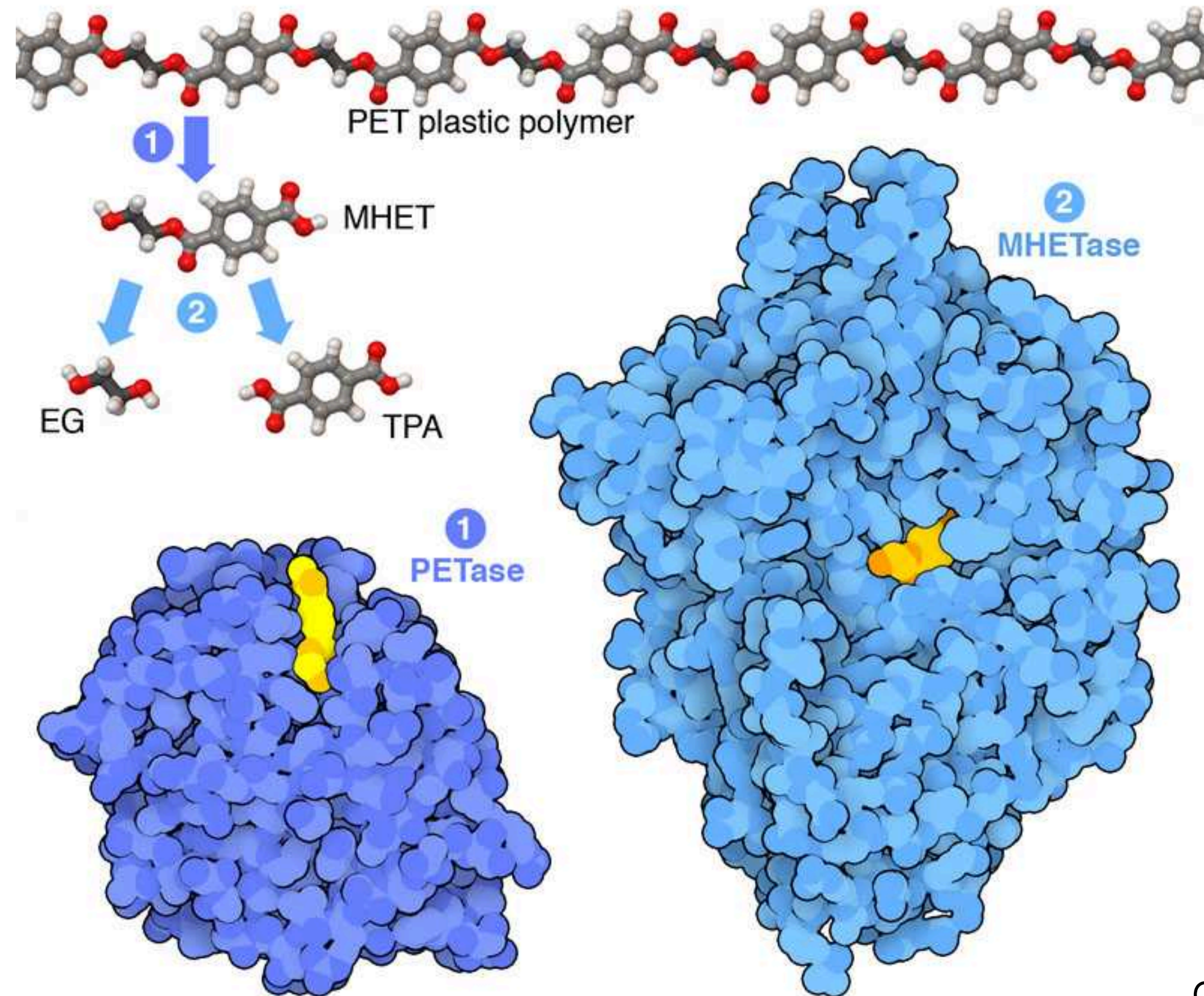


Gao et al. 2022



# Plastic-degrading enzymes

- Ambient reaction conditions
- Feedstock flexibility
- Product selectivity



Goodsell, 2023



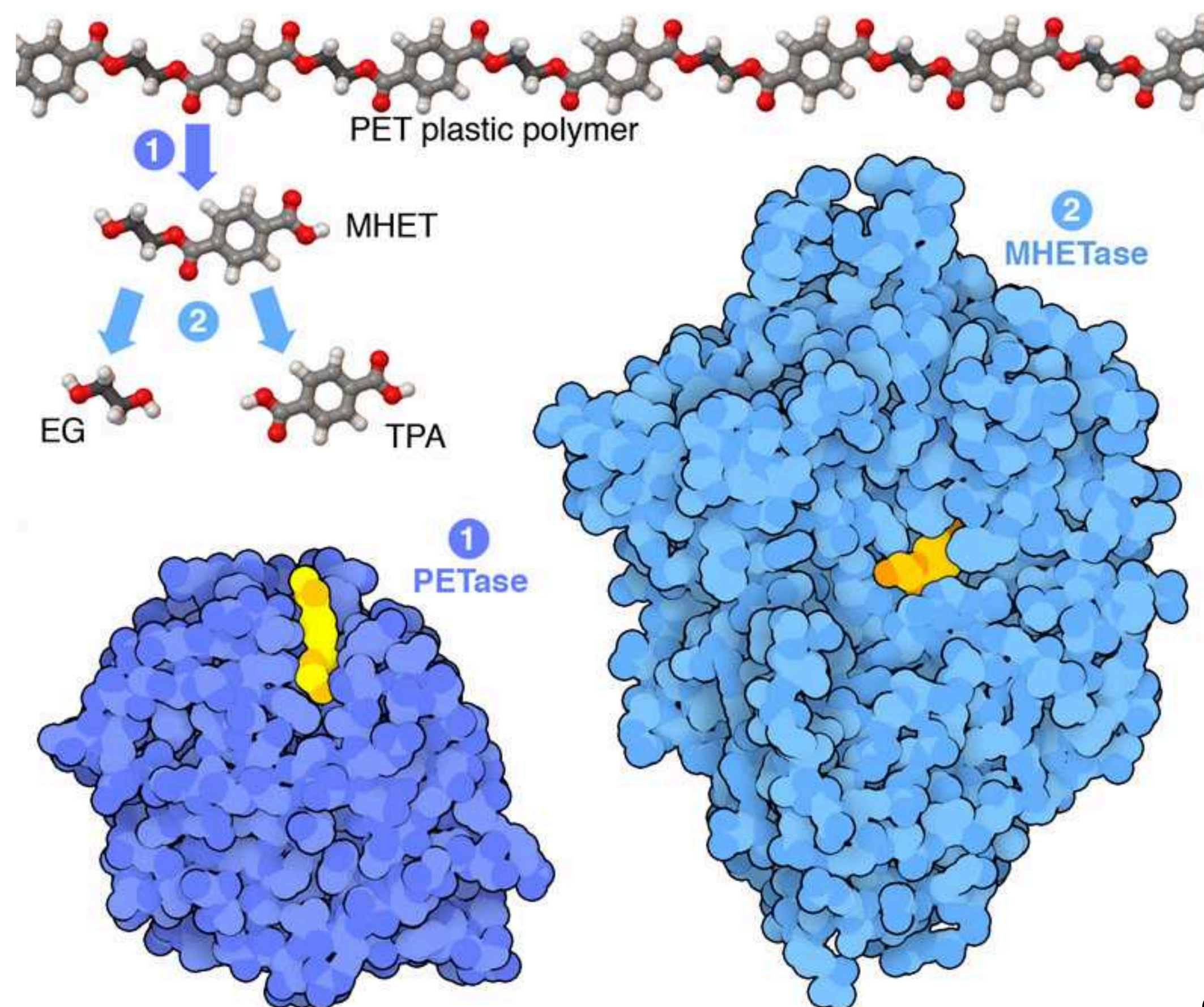
# Plastic-degrading enzymes



Feedstock availability



Product purity



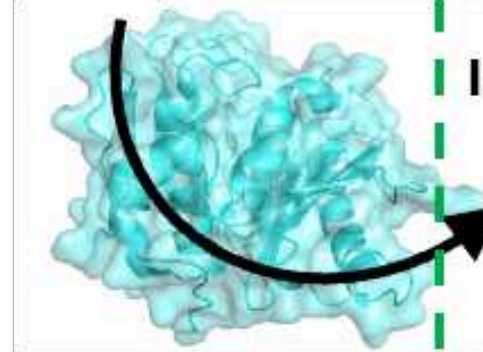
Goodsell, 2023



## PET Degradation

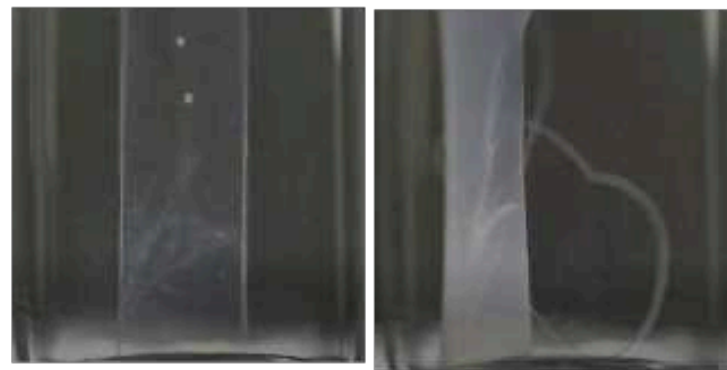


Enzymatic degradation \  
in water (60°C, pH 8)  
>95% weight loss

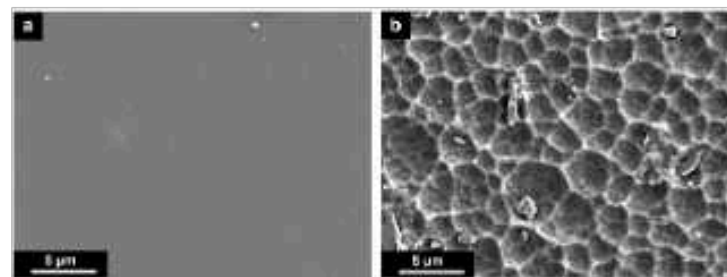


**Intermediate**  
Plastic  
monomers  
in water

By eye



Under the microscope



Before

After

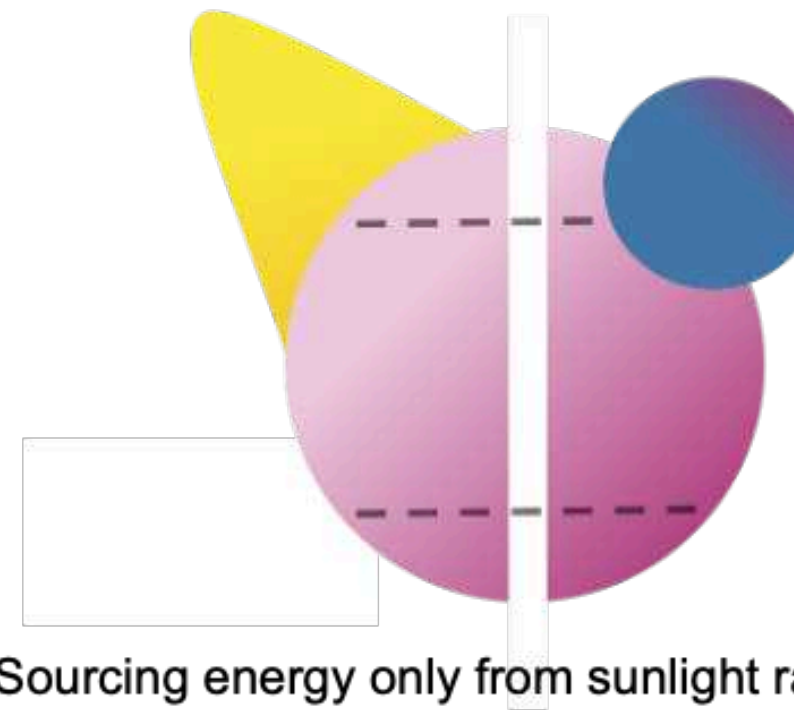
## Reforming toolbox

### 1. Electroreforming



Fusing protons rather than splitting water to generate hydrogen, hence less energy consumption.

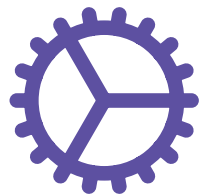
### 2. Photoreforming



Sourcing energy only from sunlight rather than electricity.



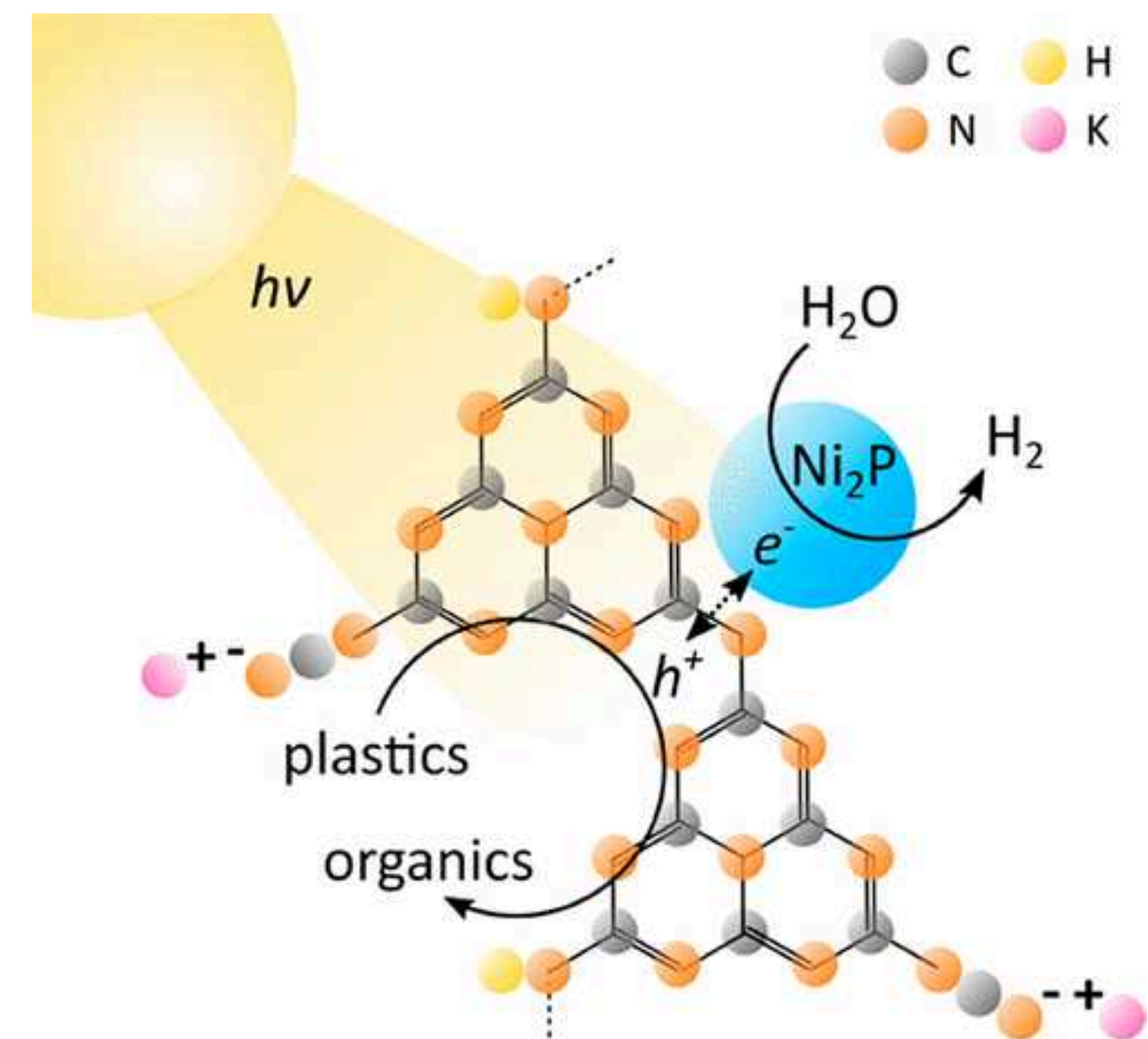
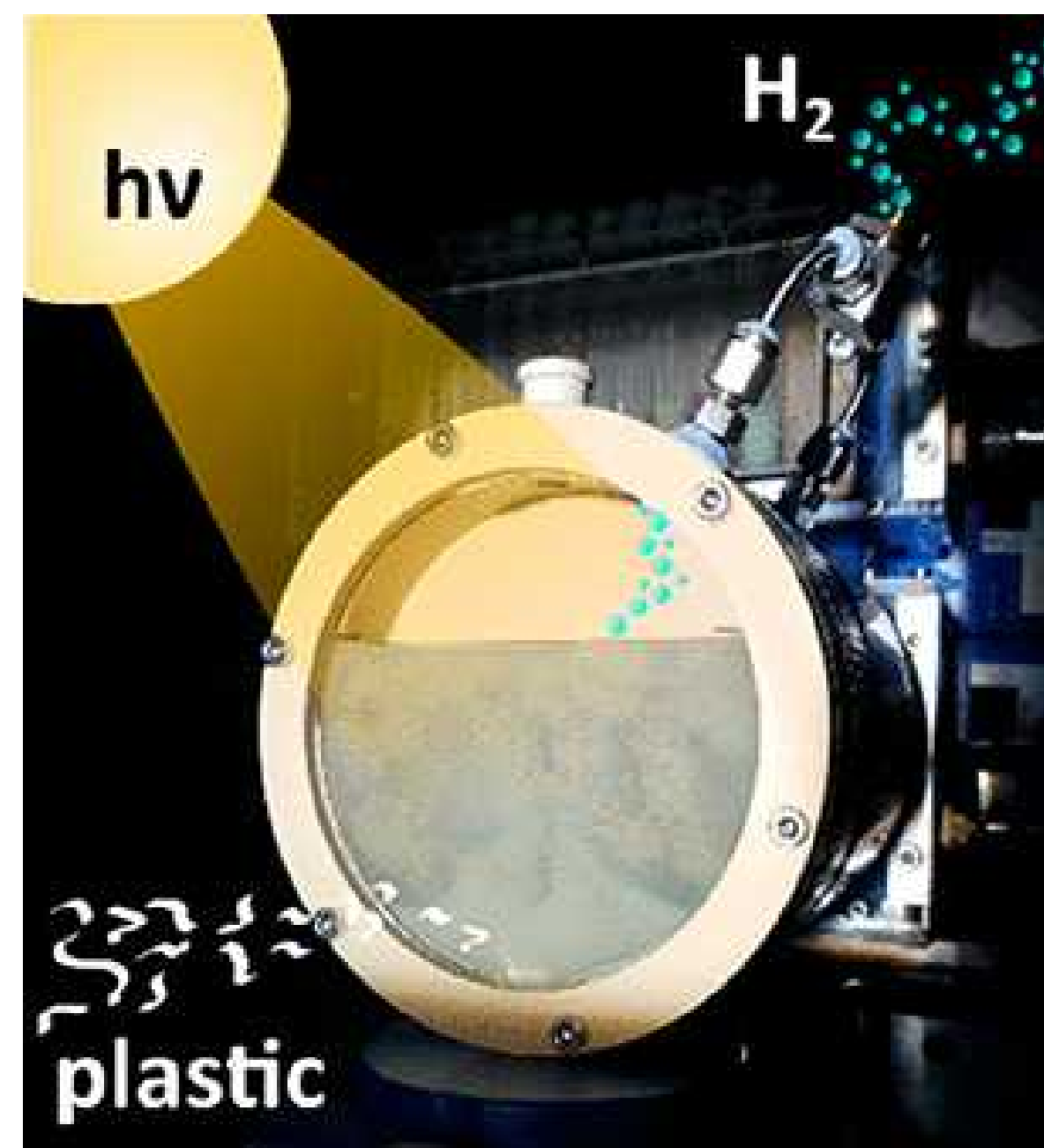
# Photoreforming



Cost and efficiency



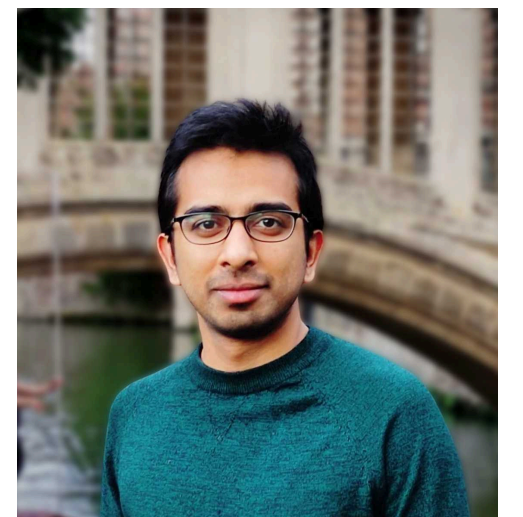
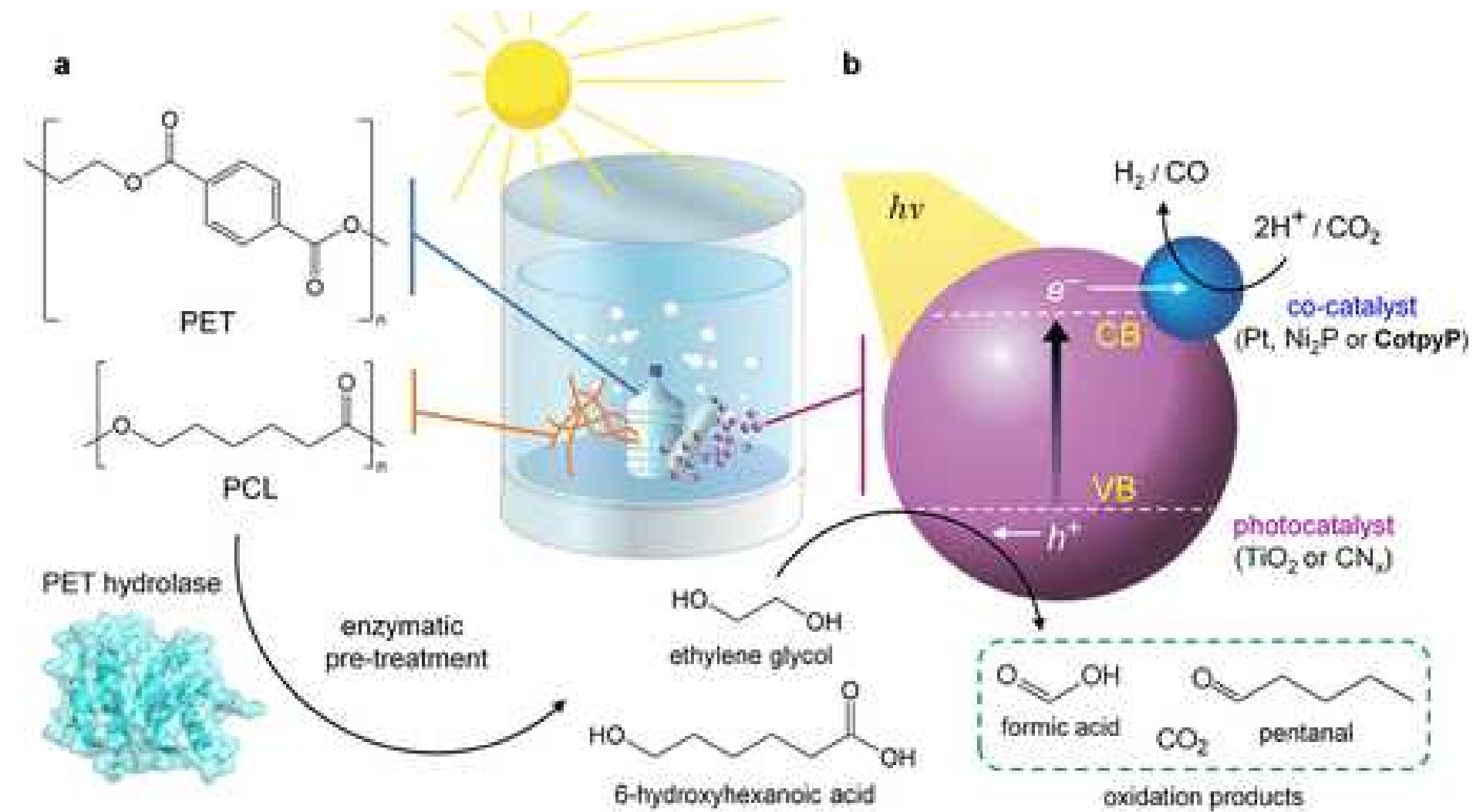
Product market fit



Uekert et al. 2019

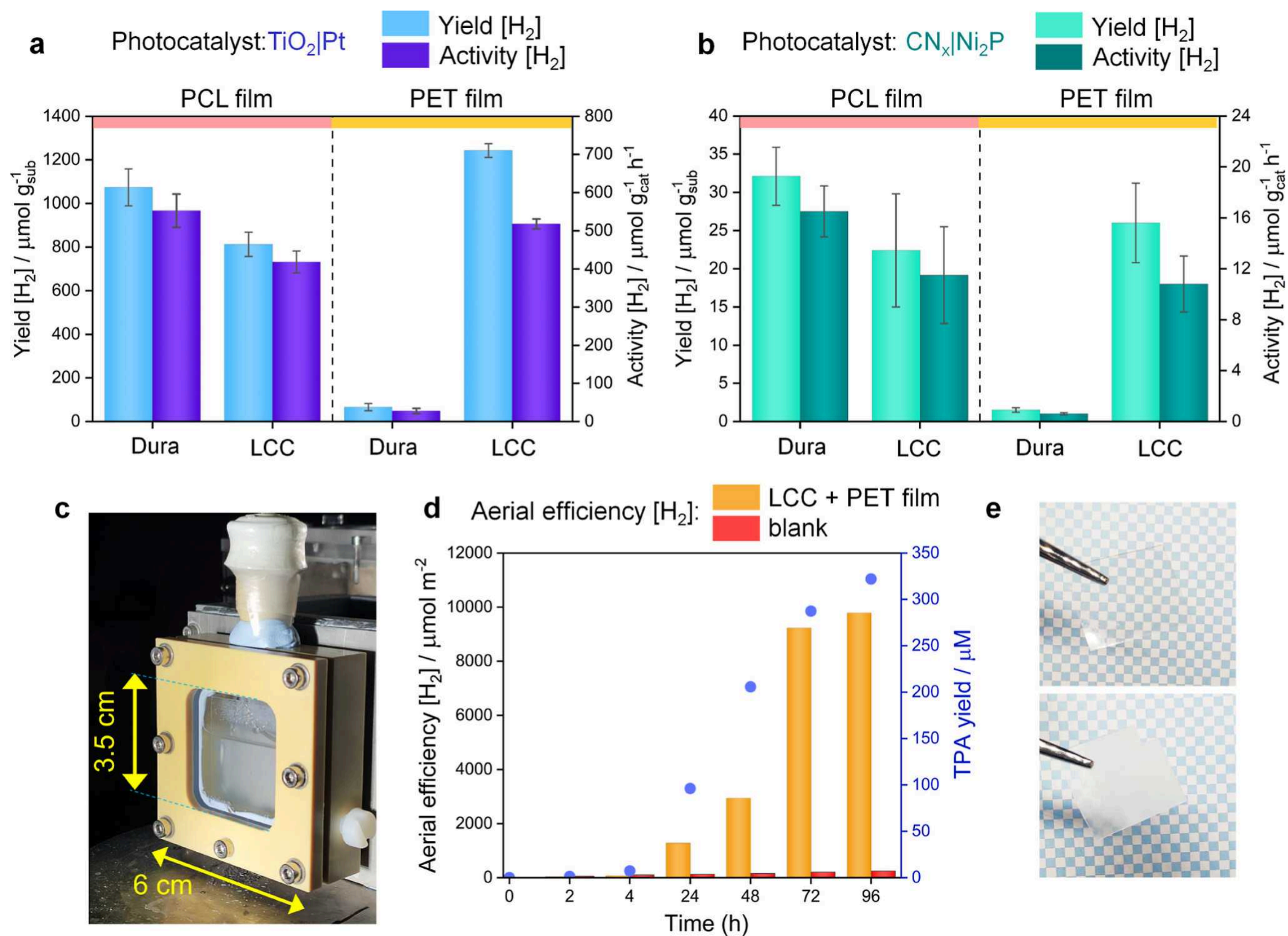


# Concurrent enzymatic plastic degradation coupled photoreforming



Guo, Bhattacharjee et al. 2023

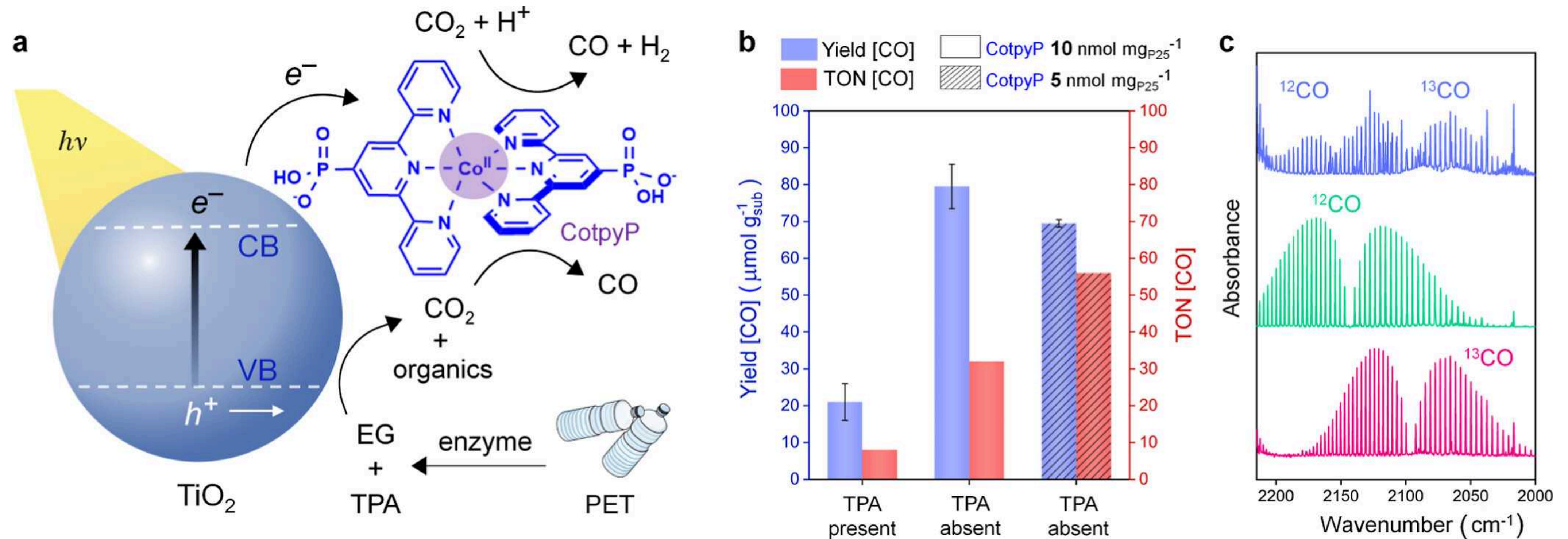




Guo, Bhattacharjee et al. 2023



# Co-catalysts create additional versatility



Guo, Bhattacharjee et al. 2023



## Kg-scale shredding and extruding



**Commercial PET wastes**

1. Shredding  
→  
2. Extruding



**Extruded PET from shredded bottles**

Shredding  
→



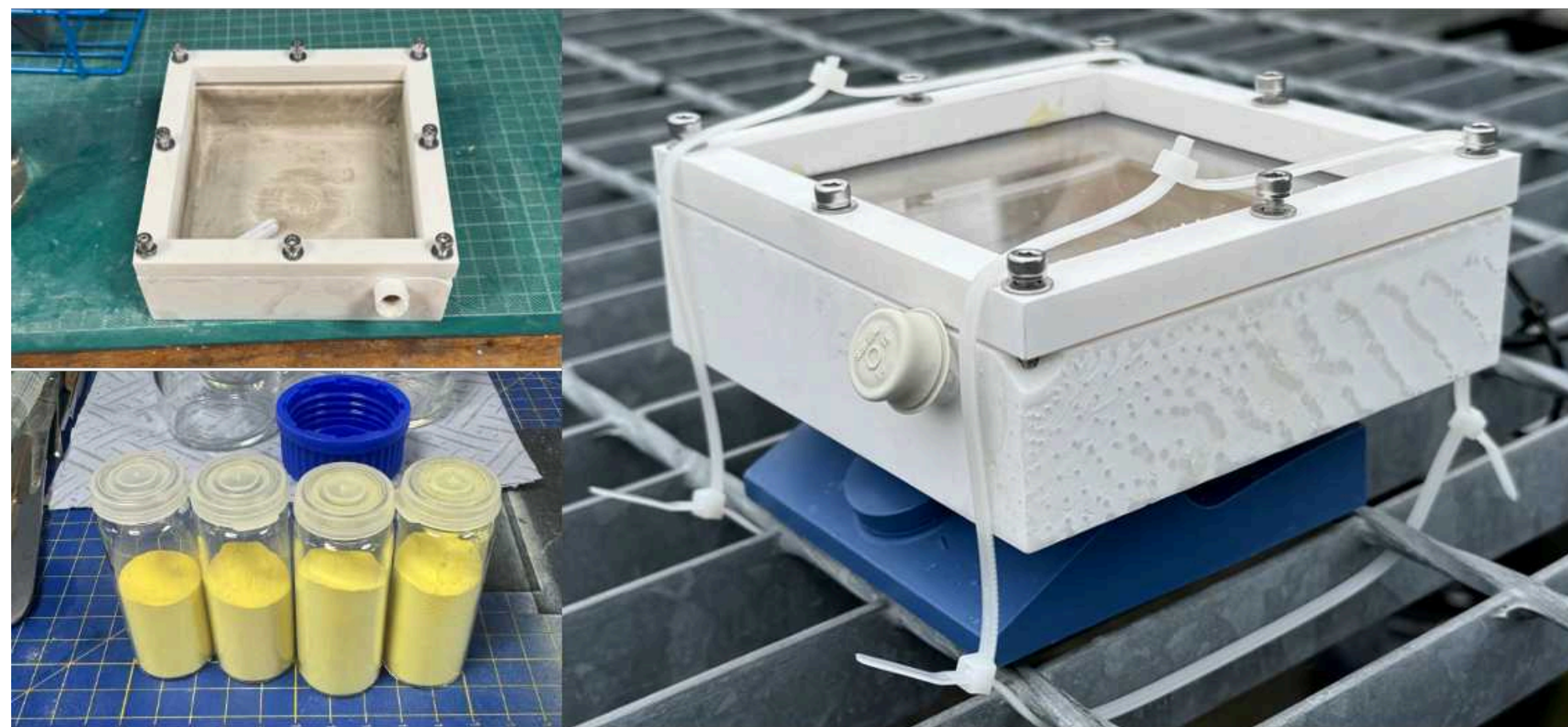
**Re-shredded PET from extruded materials**





# Work at the Department of Chemistry

1 kilograms of plastics per day as of May 2025 (TRL 4)





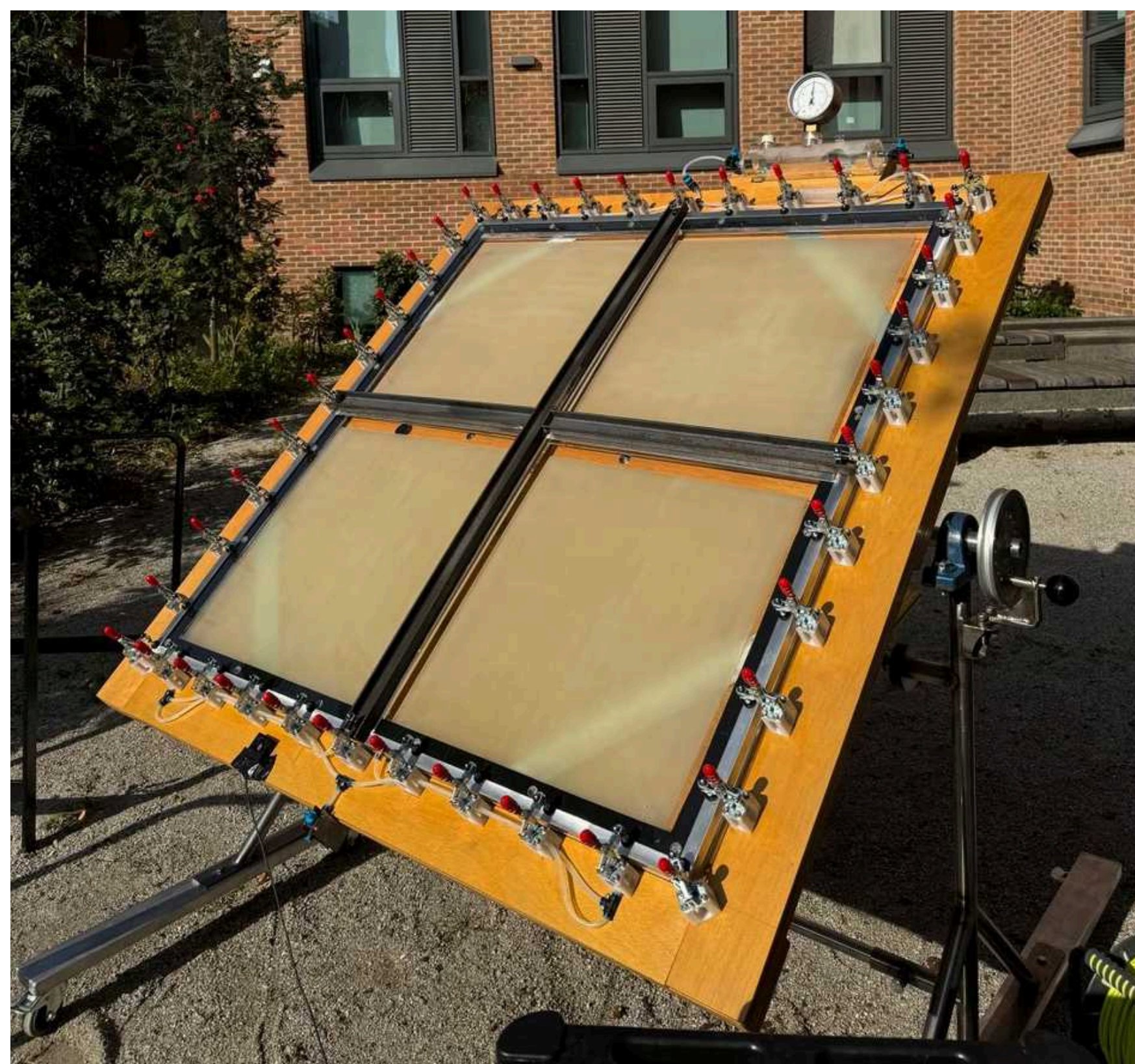
# Work at the Department of Chemistry

1 kilograms of plastics per day as of May 2025 (TRL 4)

**1-kg plastic degradation tank**



**Photoreactor panel**



**H2 zoomed in**

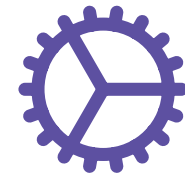




# Challenges ahead



Feedstock availability



Cost and efficiency

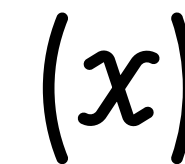
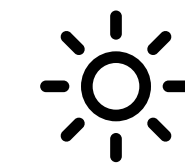
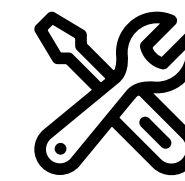


Product purity



Product market fit

- Enzyme / catalyst efficiency and stability
- Light penetration / reactor engineering
- Mass transfer, kinetics, throughput
- Integration with existing waste infrastructure
- Capital expenditure & deployment
- Market competition / regulatory risk





# Help us to unravel the value from plastics

## 500 kg waste-to-value - in partnership

- catalyst development
- feedstock expansion
- pure hydrogen off-taking
- plastic monomer and organics off-taking
- recycling facility





# Many thanks to

**Protonera team and its backers driving value from waste.**

Dr. Chan Woo Lee  
Dr. Irina Gostimskaya  
Dr. Suvendu Karak  
Dr. Ava Lage

Professor Erwin Reisner  
Professor Florian Hollfelder

Cambridge Enterprise  
University of Cambridge  
Henry Royce Institute  
Net Zero Technology Center  
InnovateUK  
Royal Society of Chemistry  
ERC PoC





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*There is no waste. There is only mismanaged resource.*



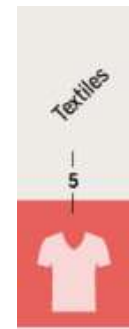
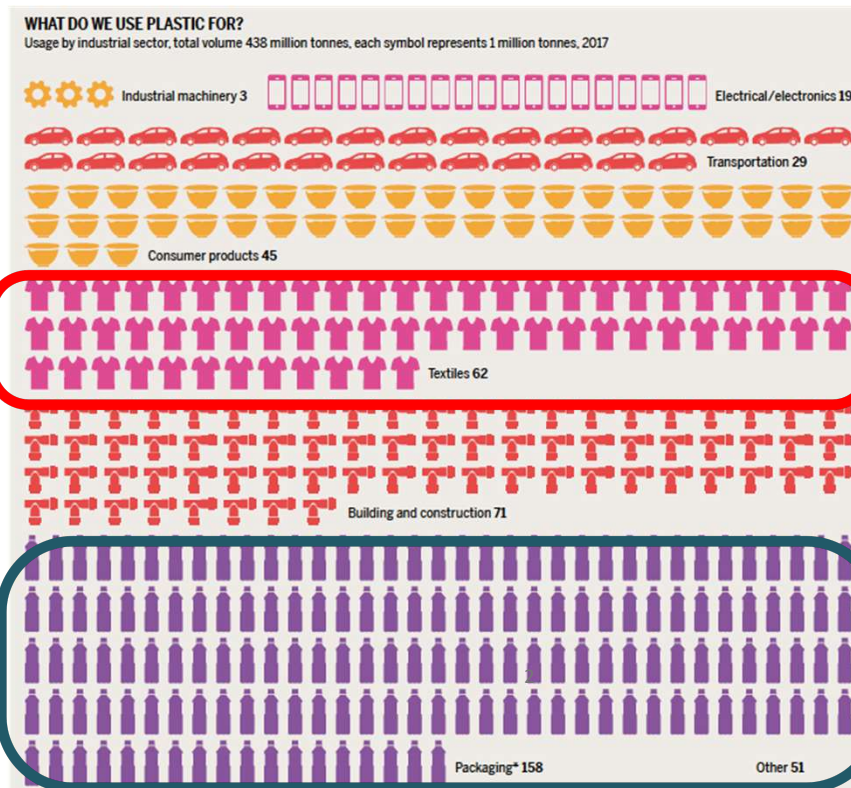
# Polymer recycling technology for the textile industry

**Professor Chenyu Du**

**The University of Huddersfield**

**4<sup>th</sup> BBNet conference, Sheffield, 15-17<sup>th</sup> Oct 2025**

# Plastic recycling

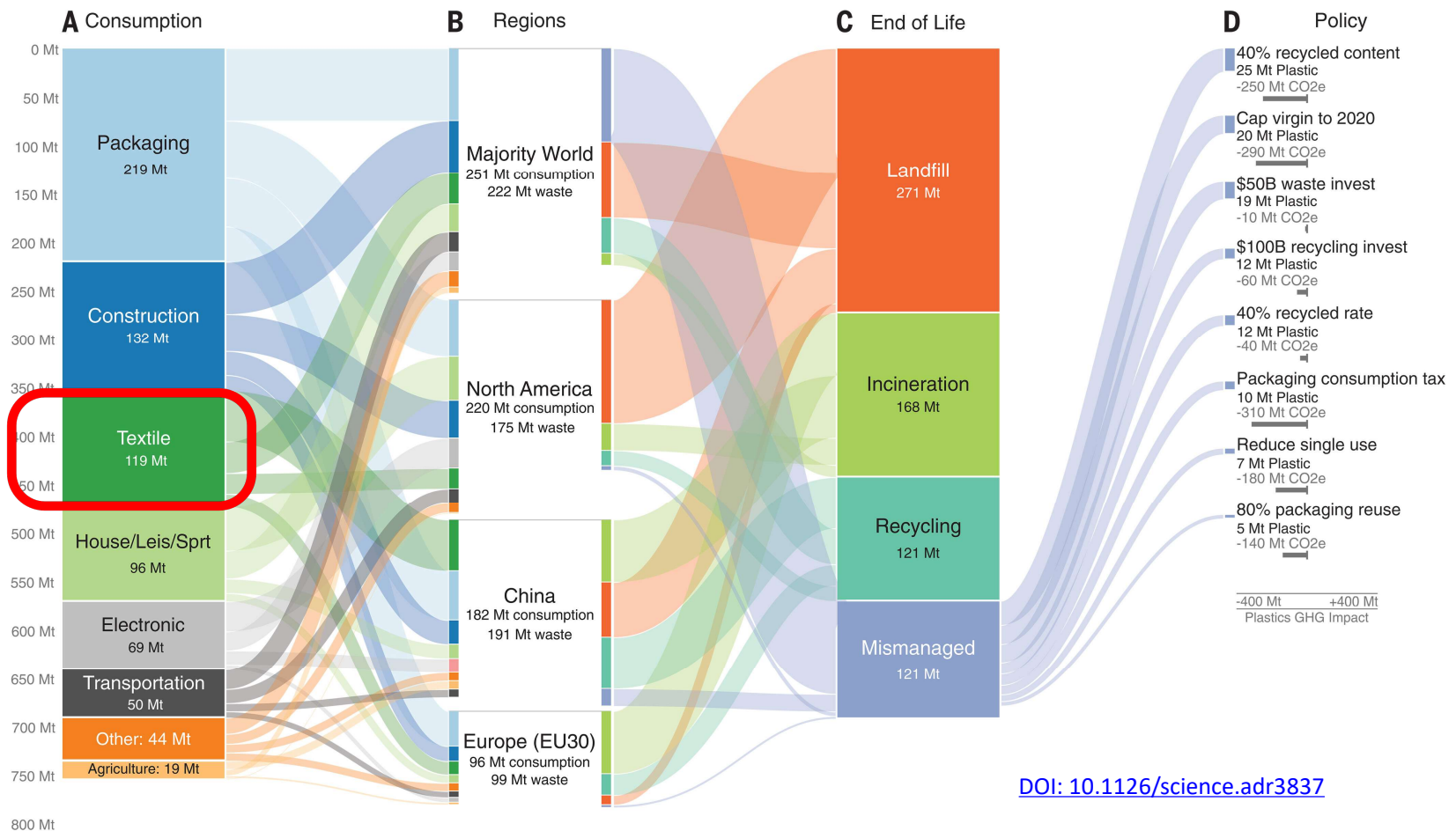


1/7

1/3

- In 2017 **438 million** tonnes of plastic have been produced
- Among them, around **1/3** has been used for plastic packaging 158 million tonnes
- Not many people realise that around **1/7** of plastic has been used in textile 62 million tonnes
- Average life-time for packaging is **0,5 years**, while average life-time for textiles is **5 years**

# Plastic recycling



DOI: [10.1126/science.adr3837](https://doi.org/10.1126/science.adr3837)



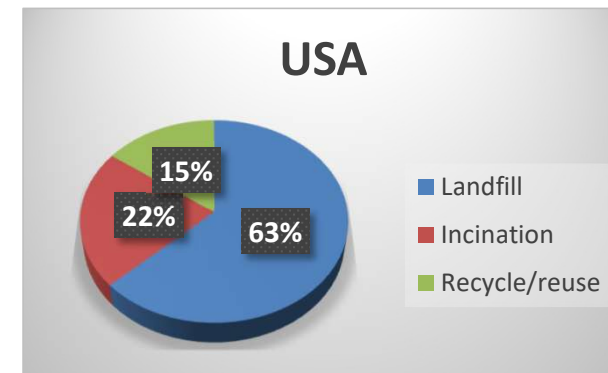
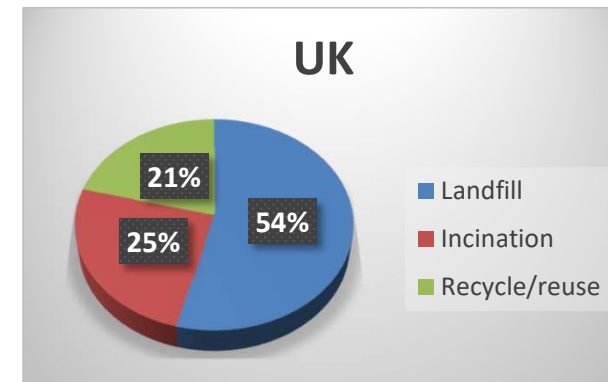
# Textile waste challenge



Worldwide  
**92 Million Tons**  
of textile waste every year

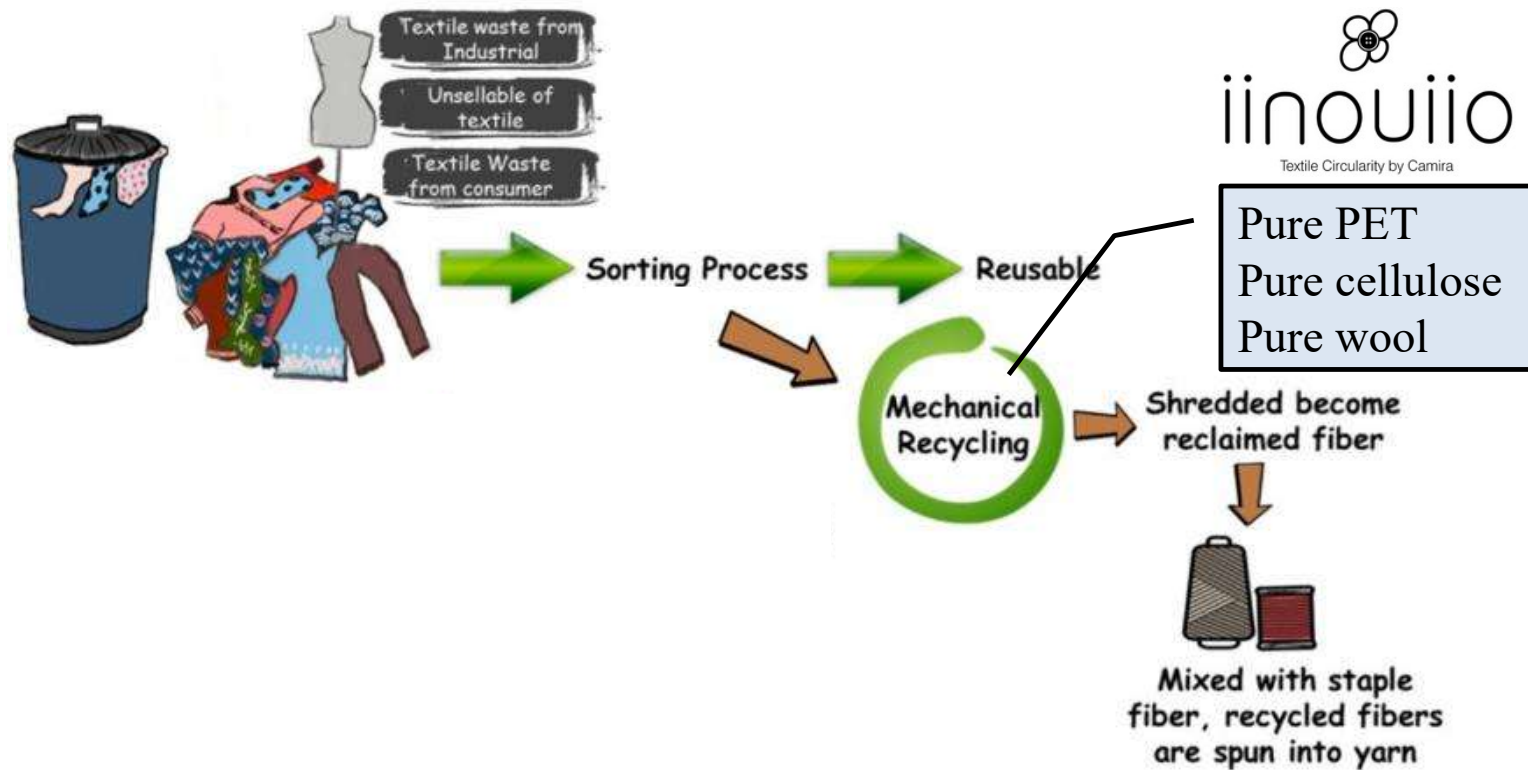


UK  
**1.13 Million Tons**  
of textile waste every year



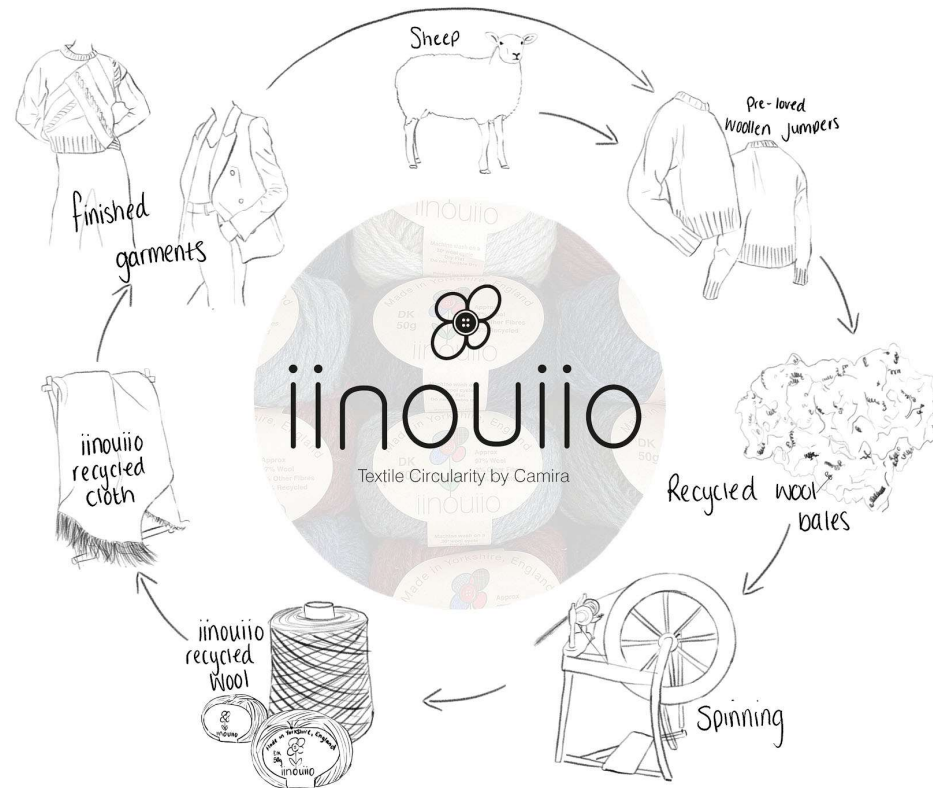
4

# Textile Waste Recycling technology



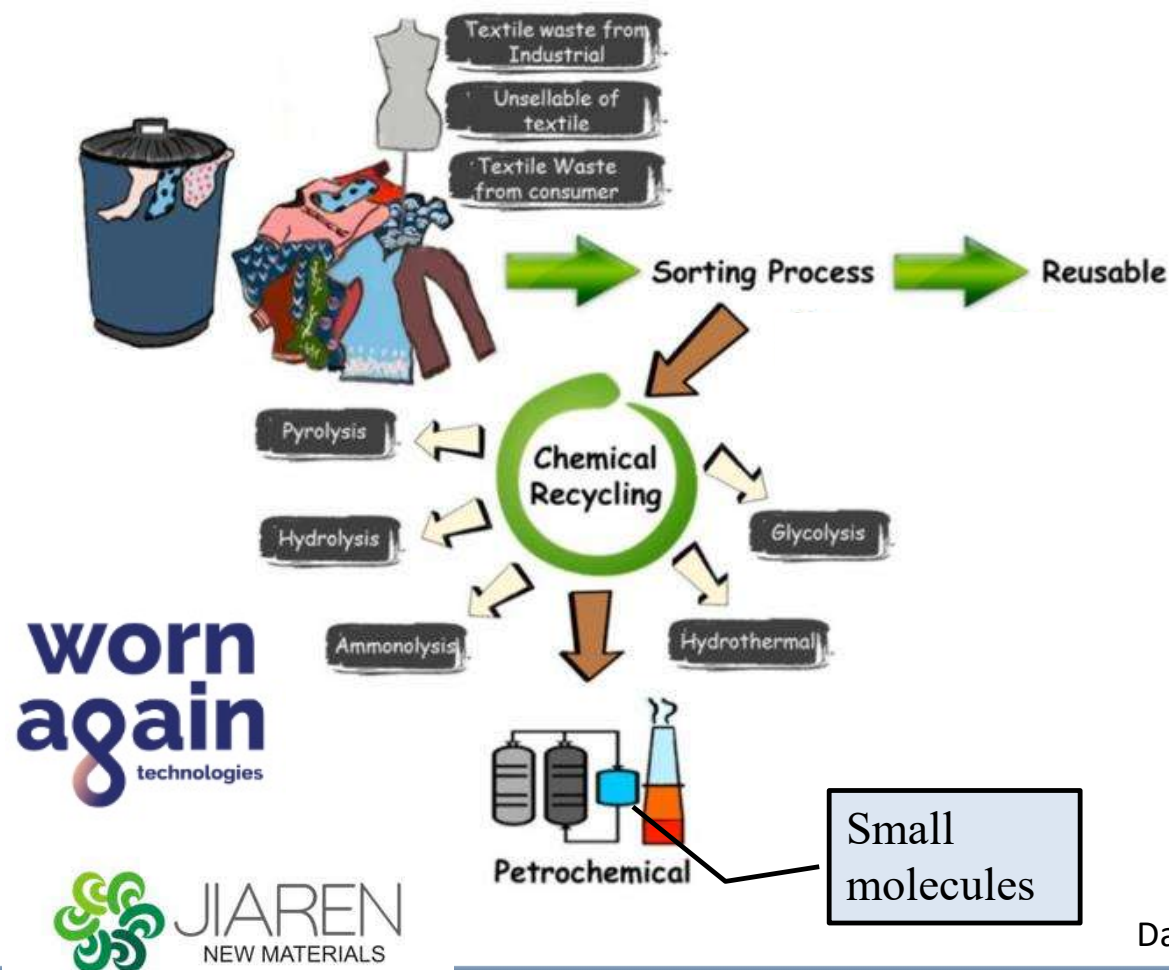
Damayanti et al., 2021 Polymers

# Textile waste mechanical recycling





# Textile Waste Recycling technology



Damayanti et al., 2021 Polymers

# Textile waste chemical recycling

**Current capacity: 50,000 tonnes annually**

- **Joint Venture Established — 2012**
- First production line: **5,000 tonnes annually (2016)**
- One of the founding partners exited in **2016**
- **Further investments and technology upgrades** followed
- First product on sale, **2021**
- Production capacity grew to **30,000 tonnes by 2023**



# Textile waste chemical recycling

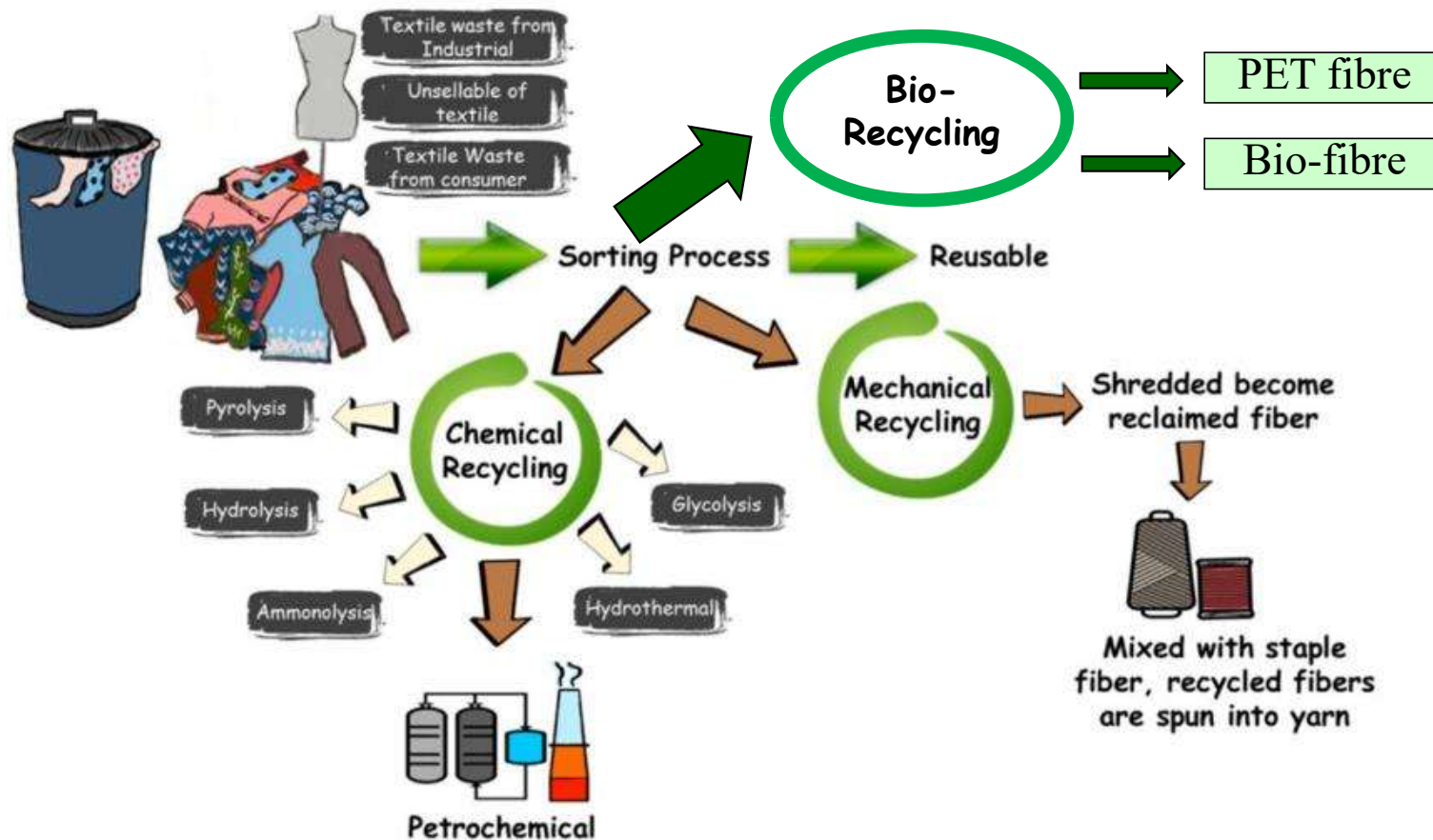


90+% PET in the textile

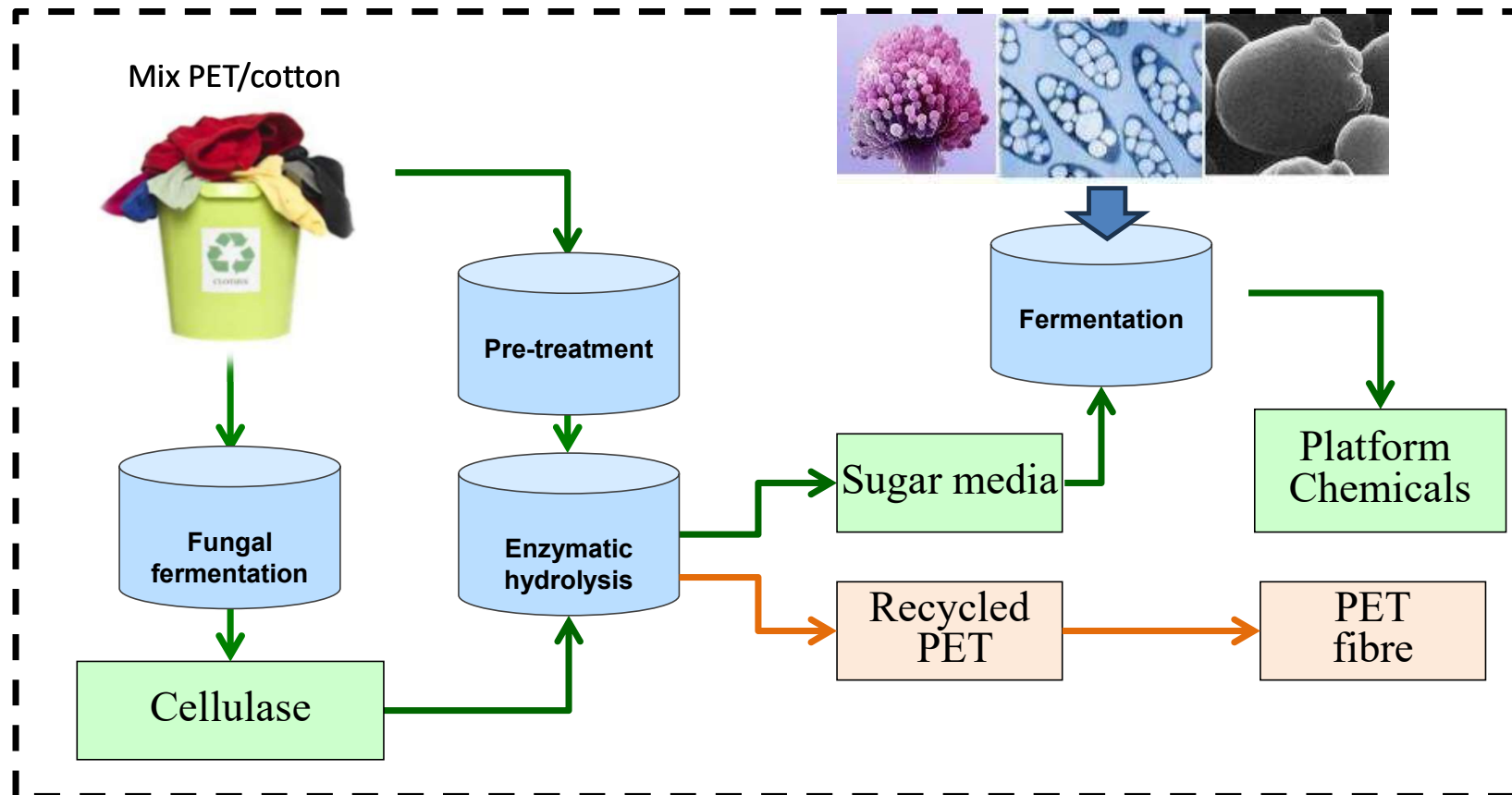




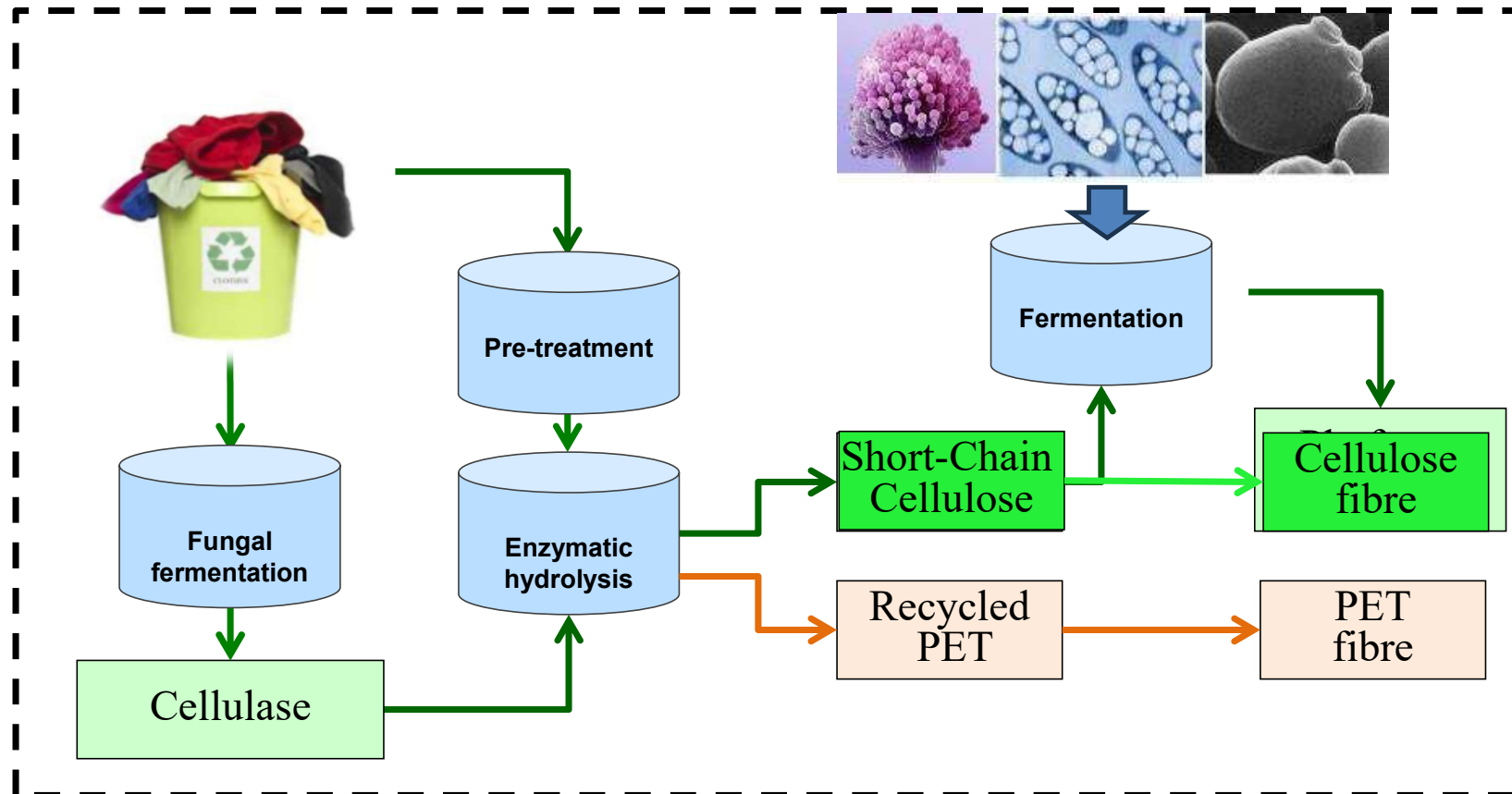
# Textile Waste Recycling technology



# Textile waste recycle - Biorefining I



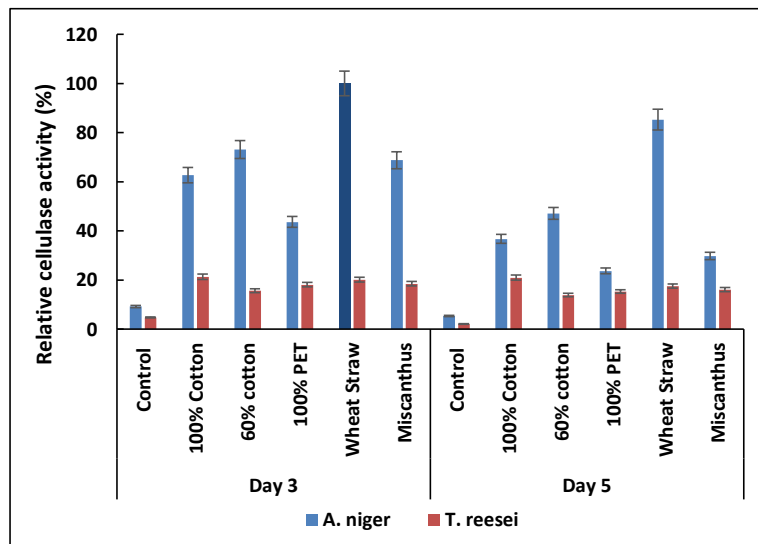
# Textile waste recycle - Biorefining II



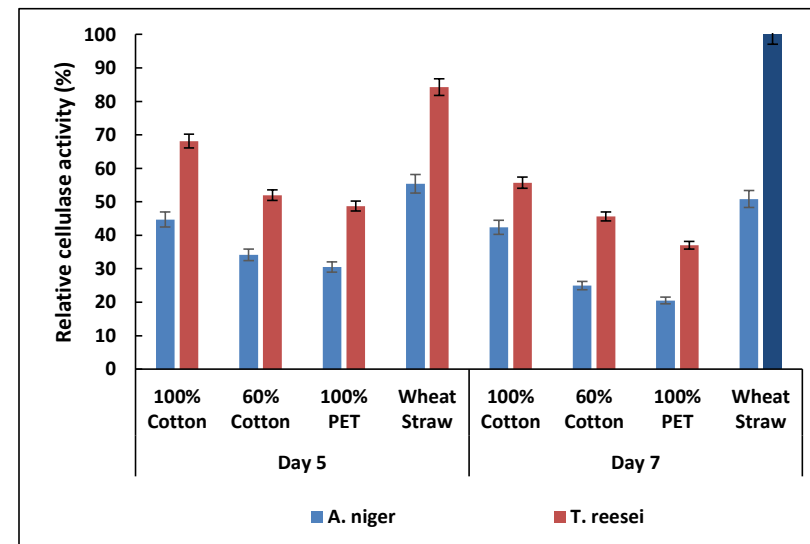


# Cellulase production

## Cellulase production using textile waste as substrate



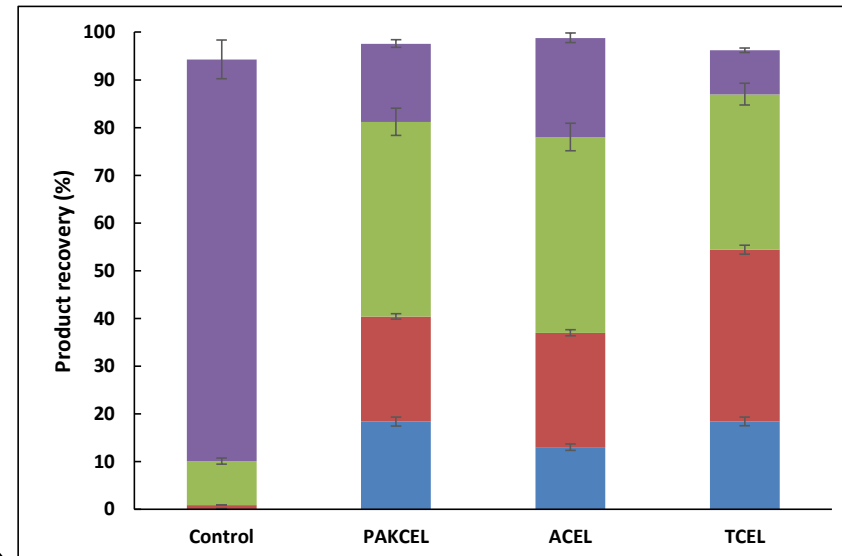
Cellulase production by *A. niger* and *T. reesei* in submerged fermentation.



Cellulase production by *A. niger* and *T. reesei* in solid state fermentation.

# Enzymatic hydrolysis

Unseparated textile waste



Recycled cotton fibre

Recycled PET fibre

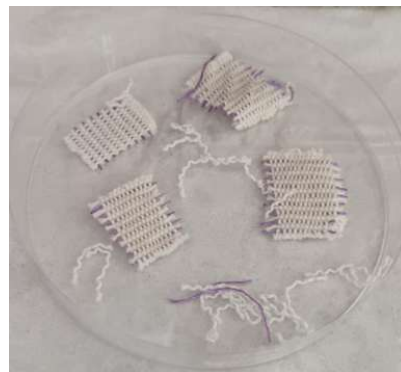
Cotton fibre

Reducing sugar

# Enzyme hydrolysis with assistant

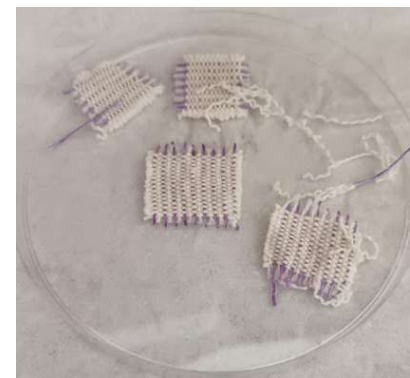


**A**

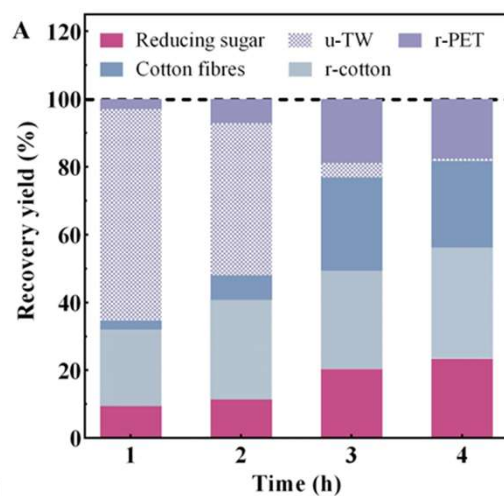


Control (no enzyme no assistant)

**B**



Plastic balls + no enzyme



**C**



Glass balls + no enzyme

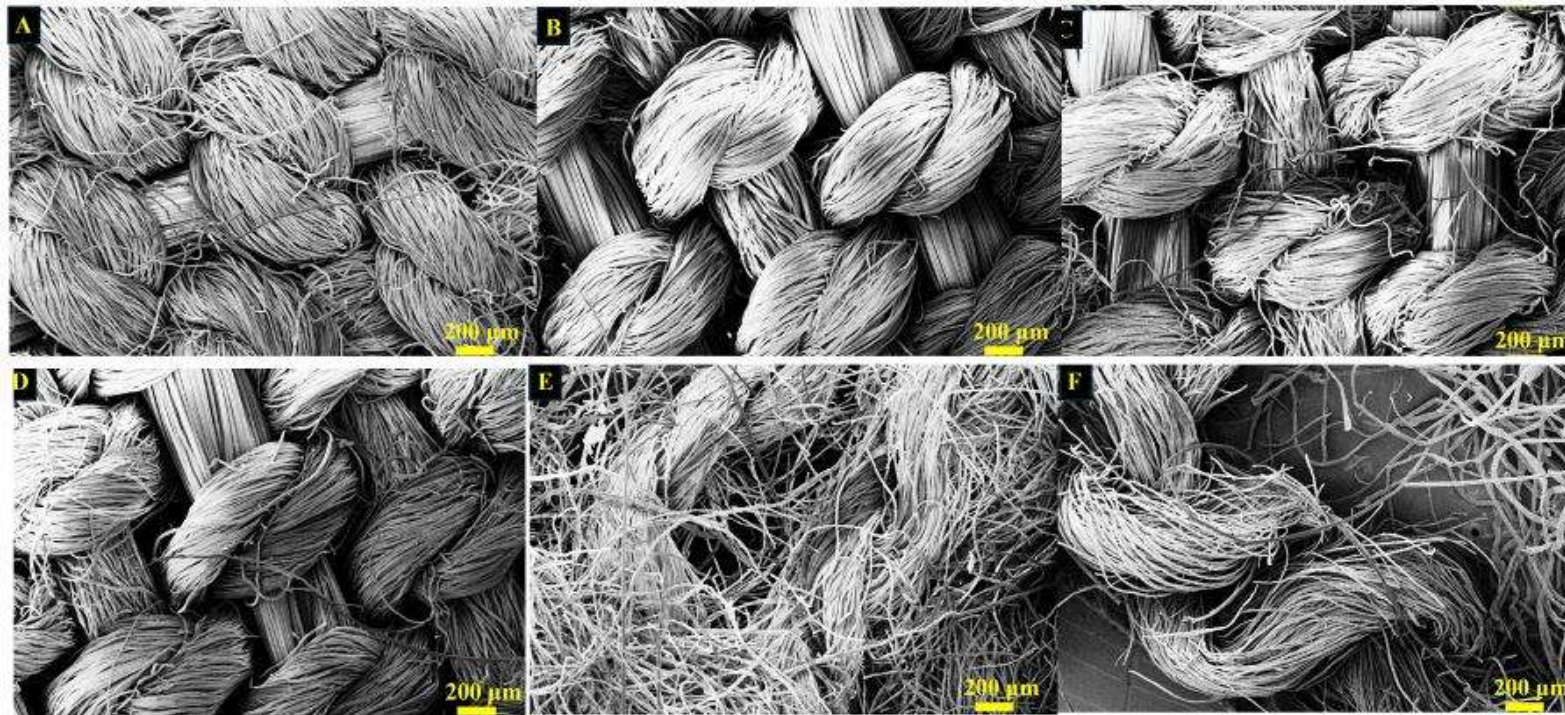
**D**



Glass balls + 80 FPU/g CTec3



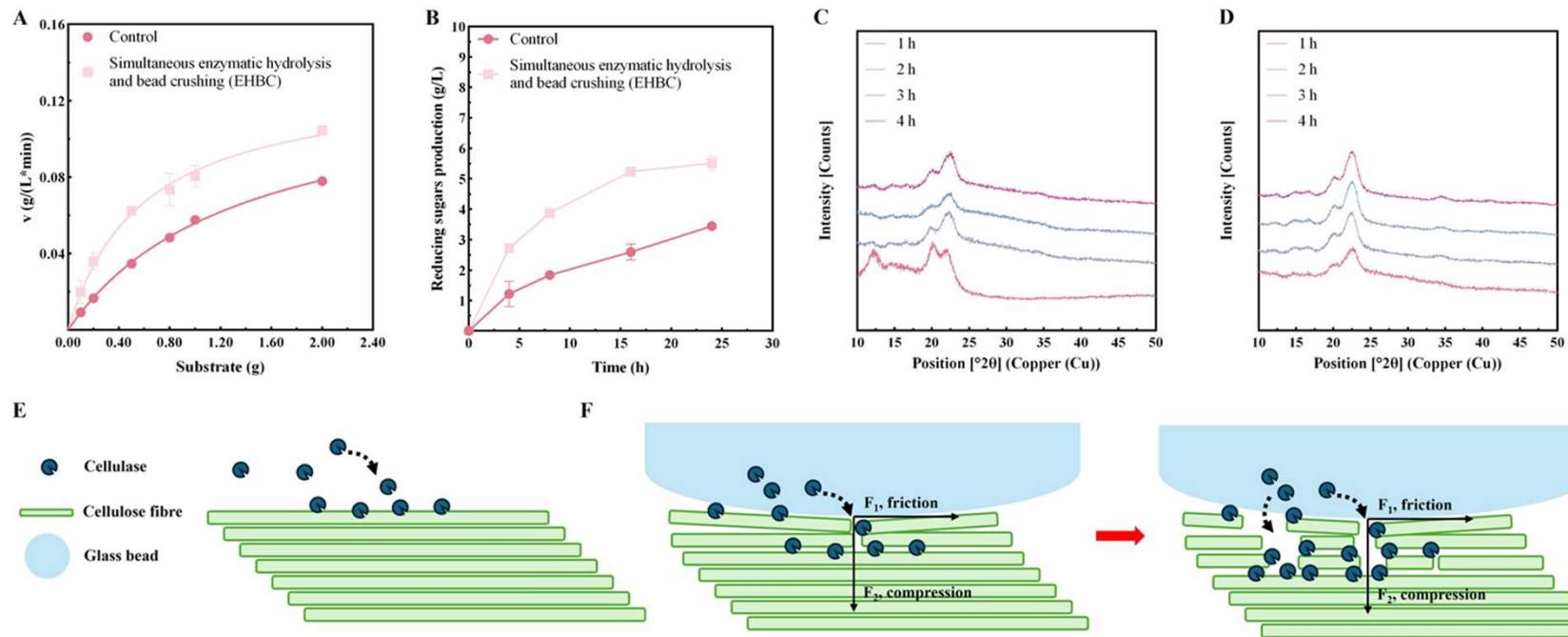
# Enzymatic hydrolysis with assistant



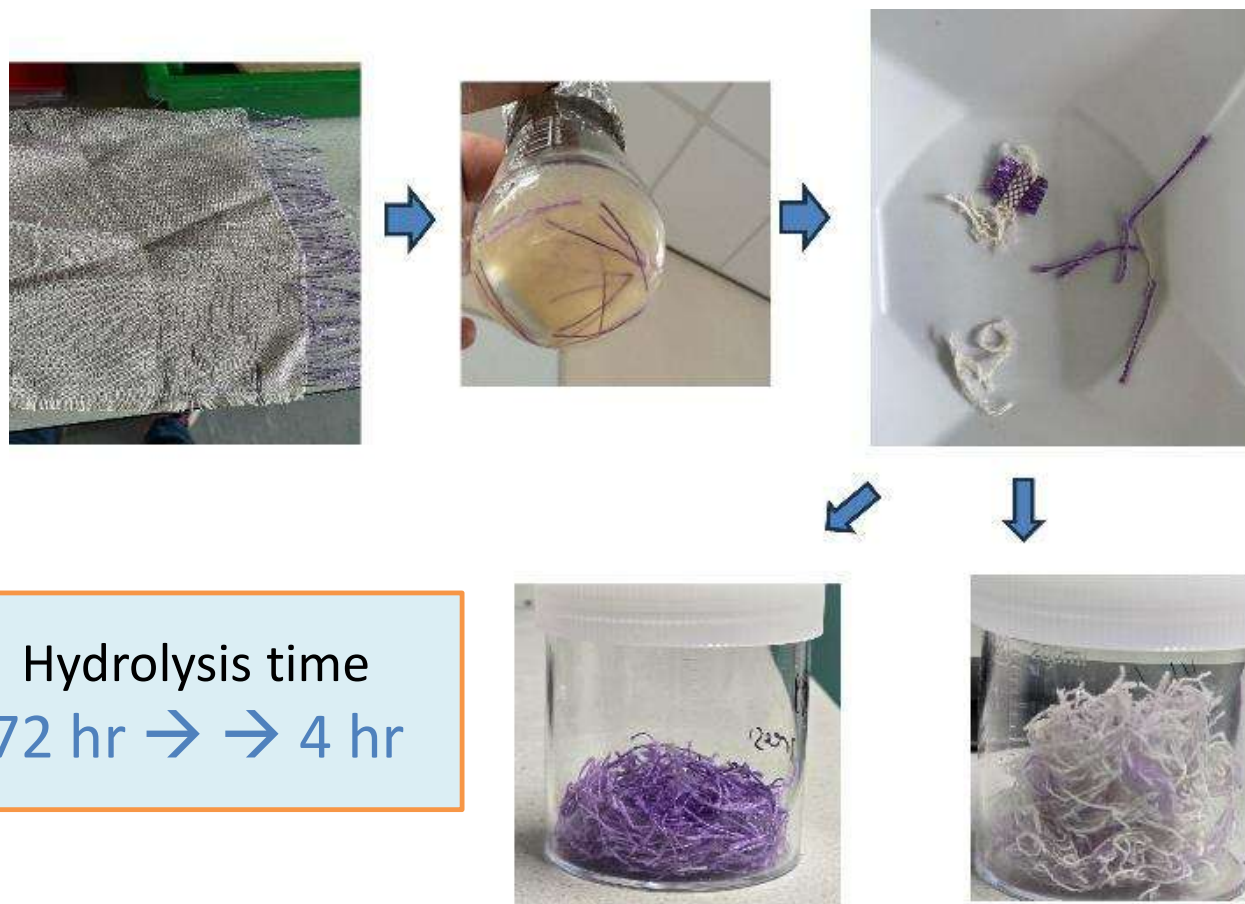
Shaking 4 h no enzyme (A). Sample after 4 h of enzymatic hydrolysis without bead (B).  
Sample after 1 h (C), 2 h (D), 3 h (E), and 4 h (F) of hydrolysis with bead

# Mechanism

Reduction in the Michaelis constant ( $K_{m\text{-control}}$ : 1.354 vs  $K_{m\text{-EHBC}}$ : 0.5823 mol/L)



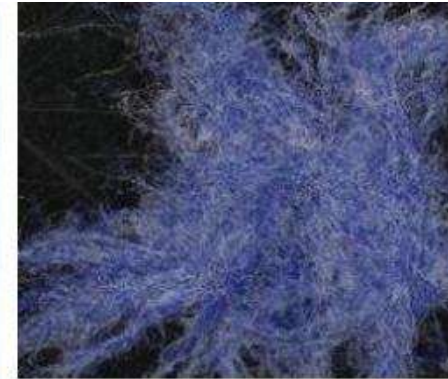
# Textile waste recycling



Hydrolysis time  
72 hr → → 4 hr

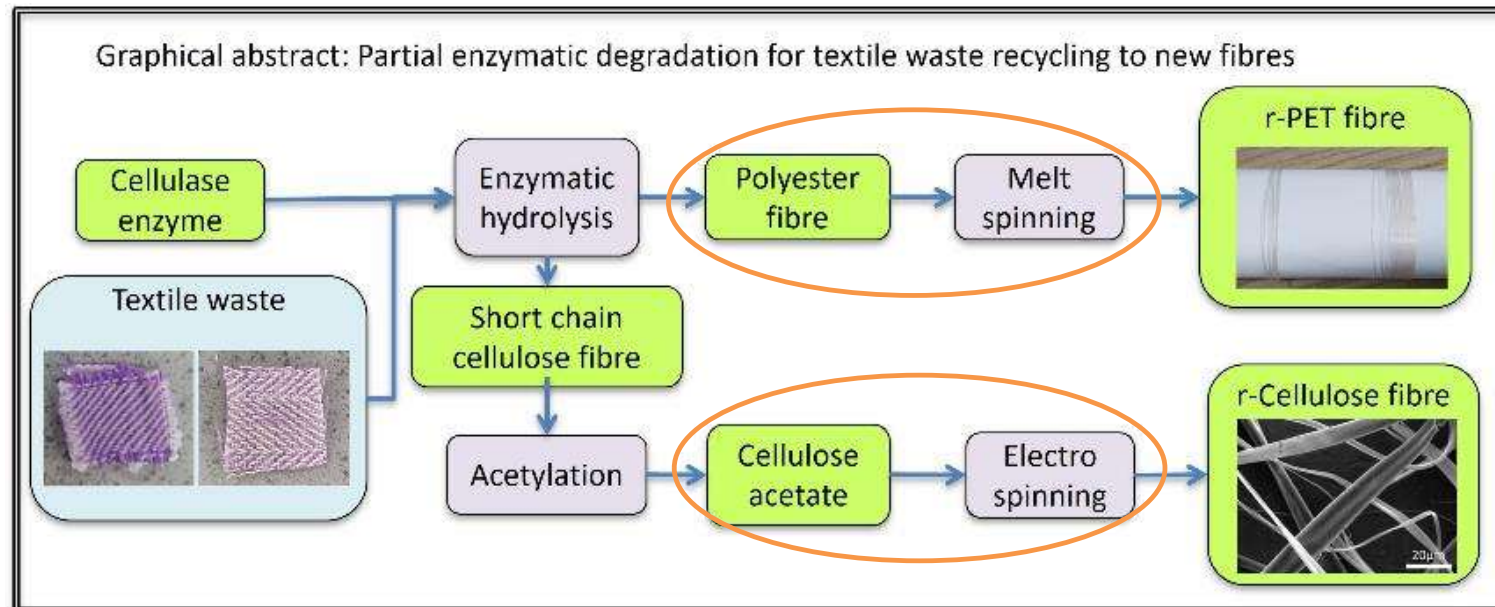


# Textile waste recycling

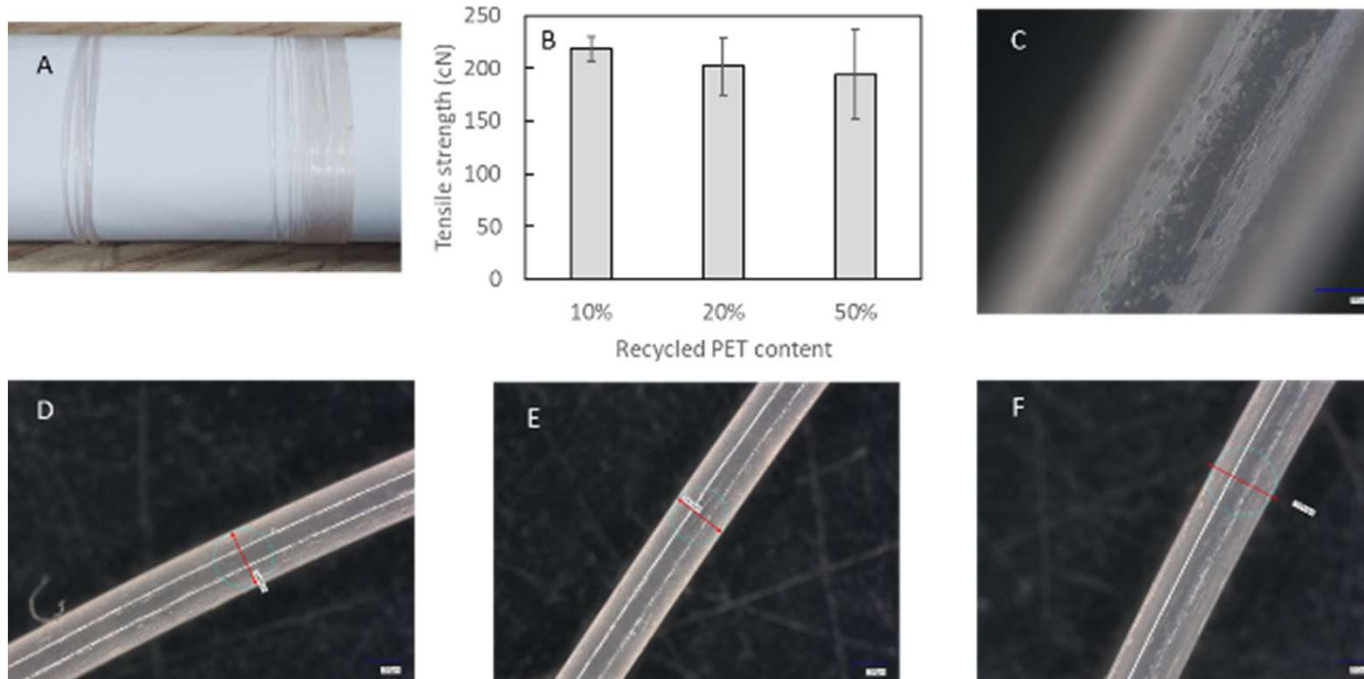


Post consumer textile waste

# Textile waste recycle - Biorefining II



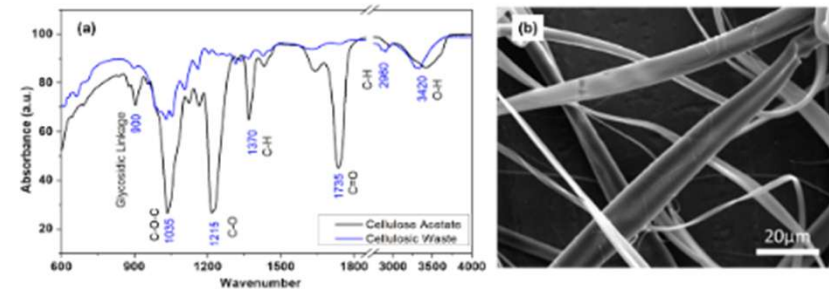
# Textile waste recycle - Biorefining II





# Textile waste recycle - Biorefining II

- 2-4 hours of enzymatic hydrolysis
- Recycled fibre yield 78.9%
- Recycled fibre cost ~£2 per kg
- Post-consumer textile waste



# Acknowledgement

## Research Team

- Dr. Andrew Hebden
- Dr. Antonia Vyrkou
- Dr. Ali Nawaz

## PhD students

- Mr. Feng Qian
- Mrs. Etini Etuk
- Miss Gargi Dandegaonkar
- Miss Ashitha Karayil
- Mr. Philip Wickramarathna Vidanelage
- Mr. Ziyao (Frost) Liu



# Acknowledgement

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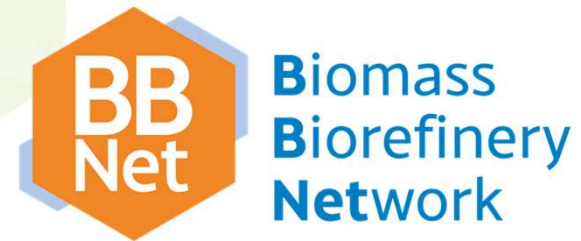
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