Green Chemistry for a Circular Economy

Public symposium - Espoo, Finland

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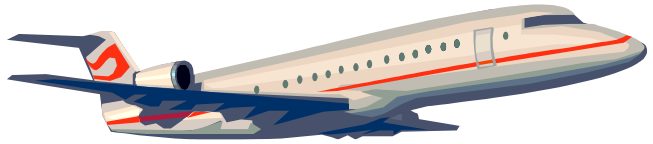
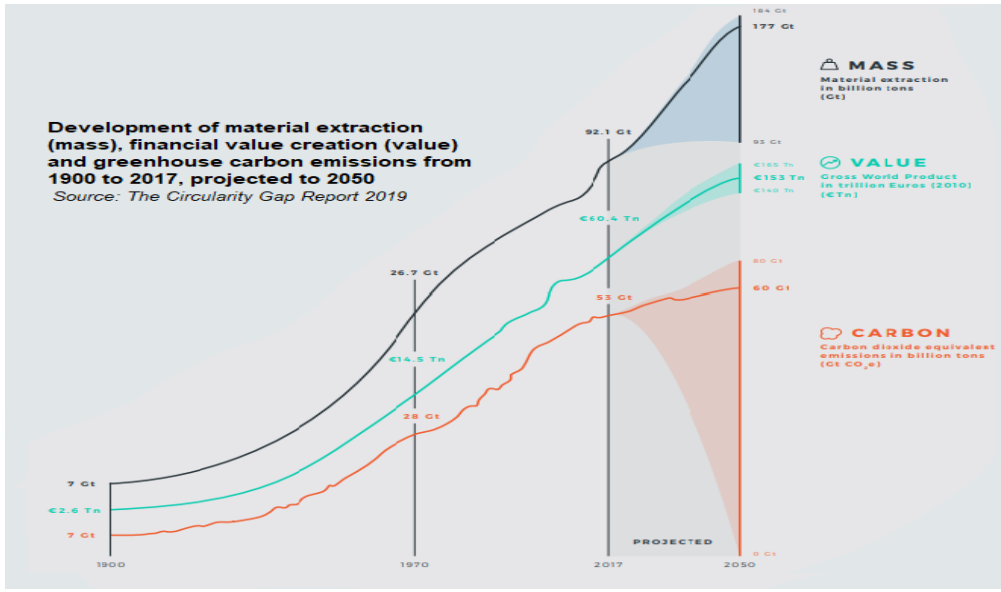
The articles of a modern society

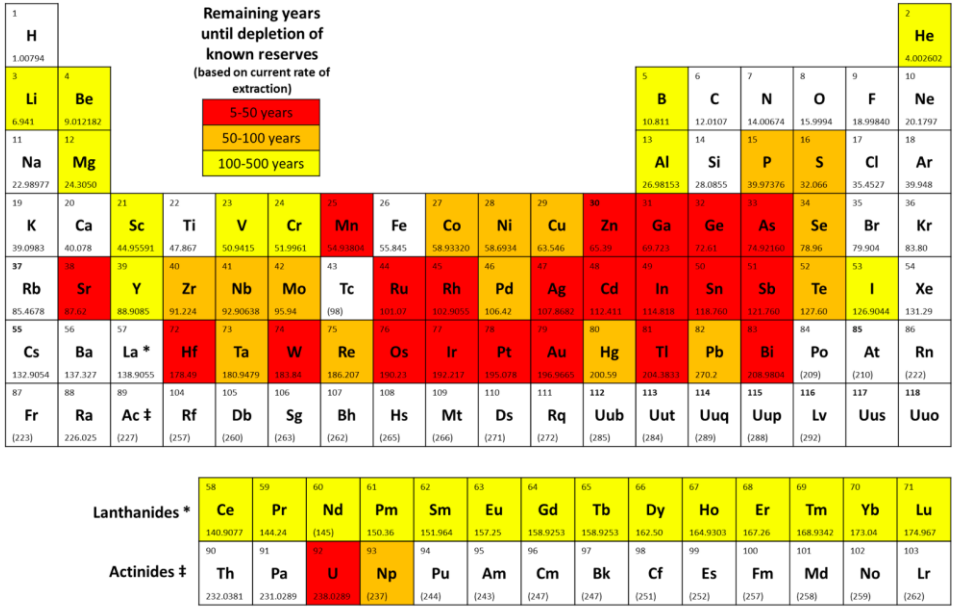


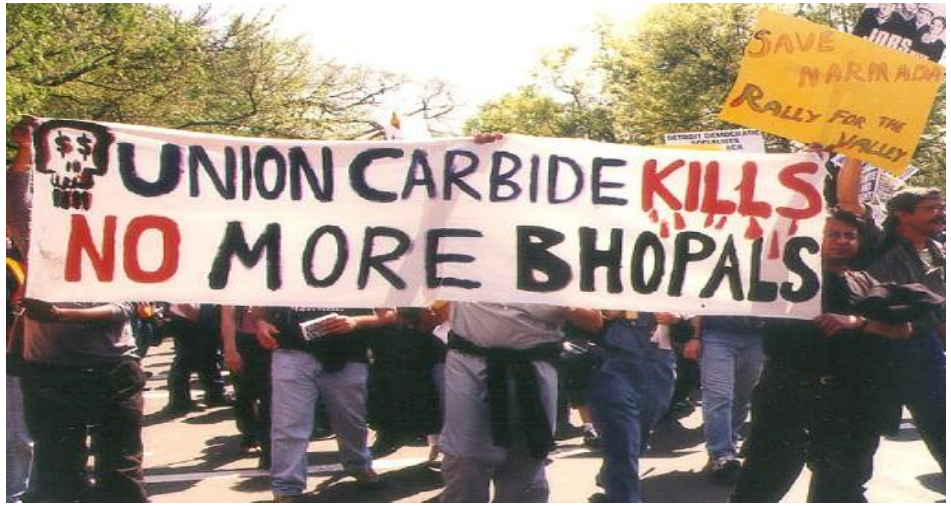


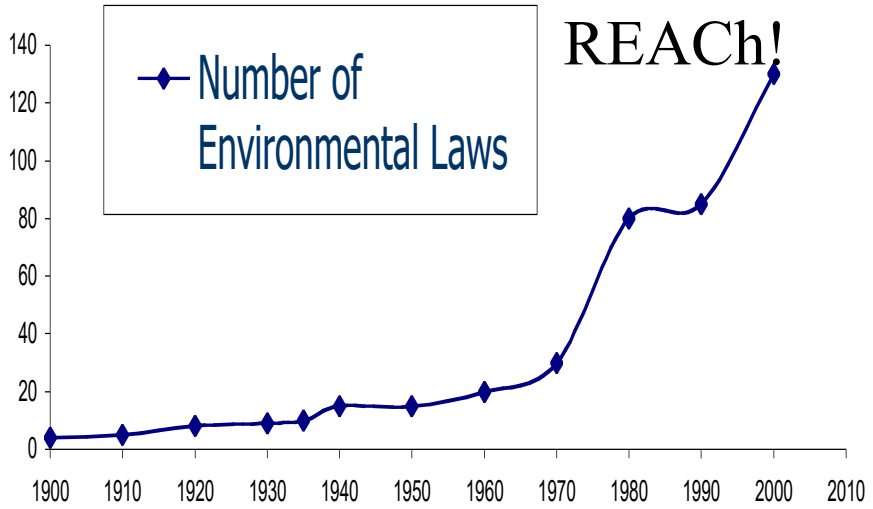
ALL items contain molecules and most rely on carbon (organic molecules)
But existing supply chains are unsustainable – in resources and processes

We are using non-renewable, diminishing resources, making more waste than product, and using dangerous substances

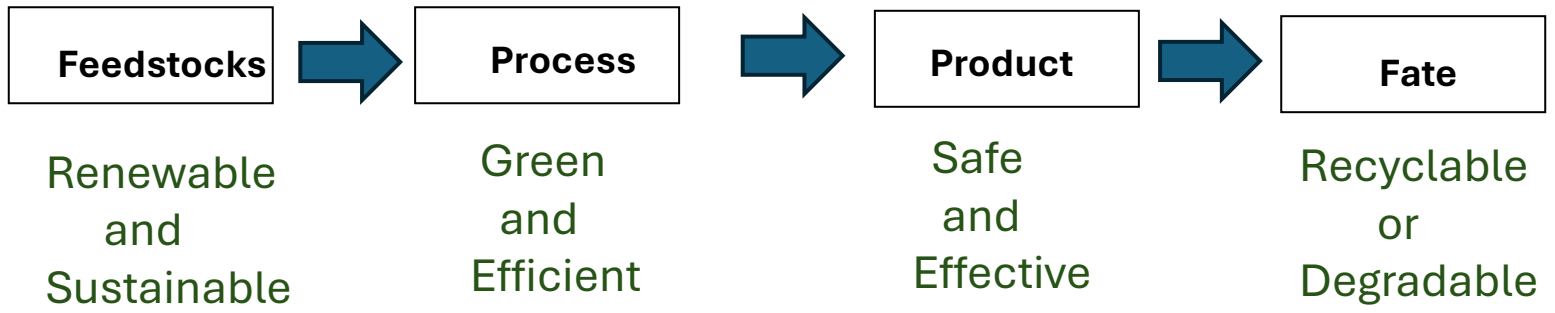
Industry	Product tonnage	Kg by-products / Kg product
Oil refining	10^6 - 10^8	< 0.1
Bulk chemicals	10^4 - 10^6	1 - 5
Fine chemicals	10^2 - 10^4	5 - 50+
Pharmaceuticals	10 - 10^3	25 - 100+







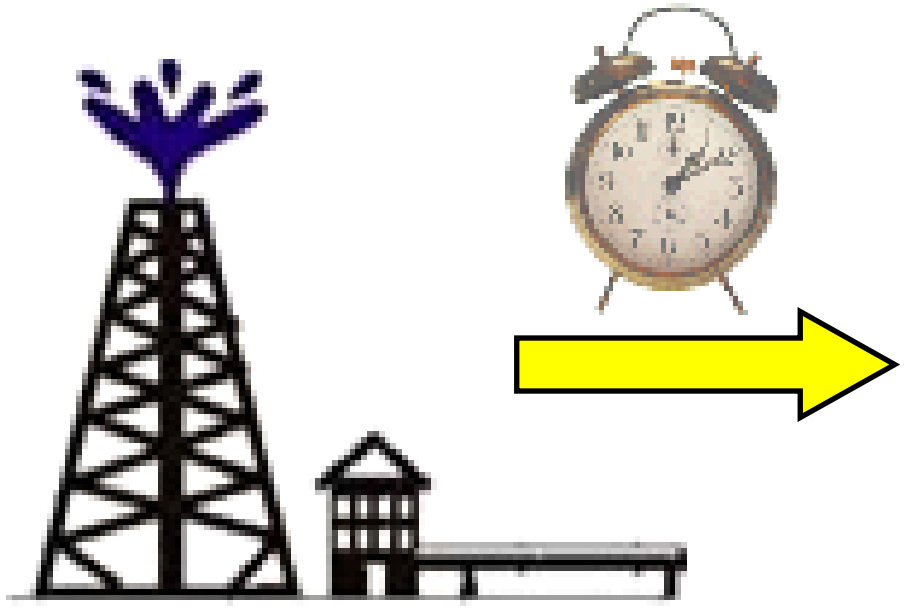
Pressures across the whole lifecycle of chemicals including polymers



Can we move away from a (non-sustainable) Linear model?

Addible.
Solutions to Complex Waste

Time is running out for traditional fossil feedstocks



100 MT of textile waste

0.5 bn T plastic waste

1 bn new tyres every year

1 trn Kg of biomass every year

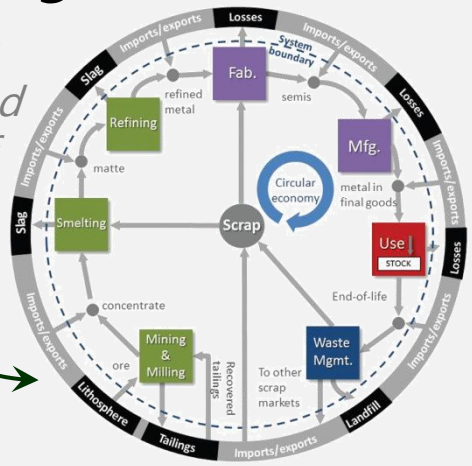
Finite virgin resources → **Circular resources**

Our future infinite Molecular resources are what we now call waste including biomass

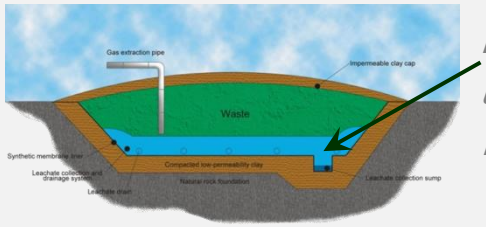
Like with carbon we need to look at using wastes as a resource for metals

Mining Waste

Metal containing waste is produced at every stage of mining.



Landfill Mining



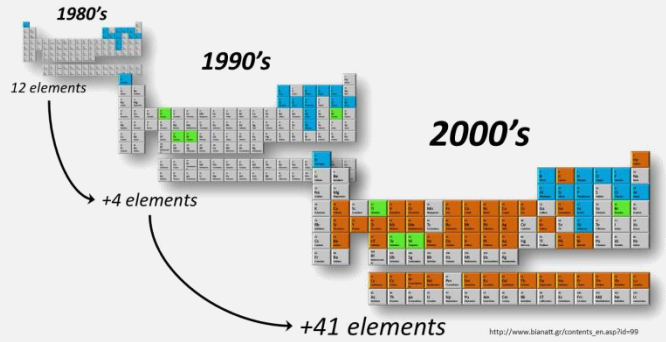
Landfill leachate is easily collected from landfill sites

> 40 metals identified in landfill leachate

Zn	Fe	Cu
10 g/L	5.5 g/L	10 mg/L

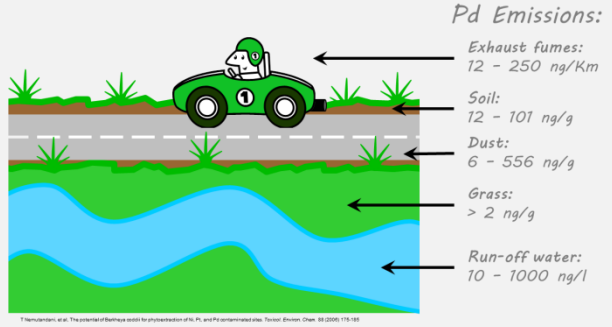
WEEE Waste

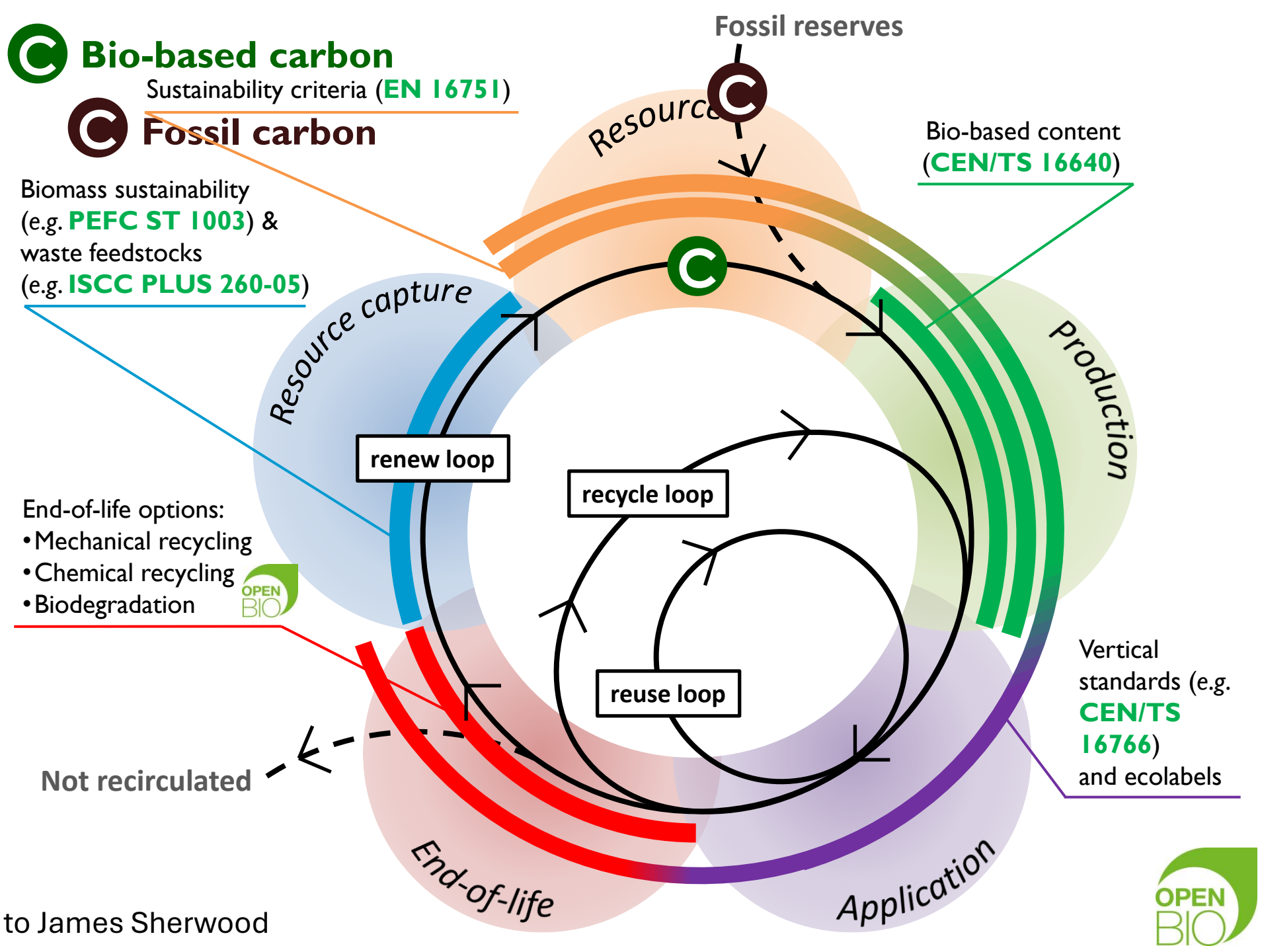
"waste electrical & electronic equipment"
Modern EEE require up to 60% of the periodic table:



PGM's from roadside dust

Up to 80% of PGM's are released from catalytic converters during their lifetime





Thanks to James Sherwood

Renewable resources yes - but not any biomass

Palm oil:

- ✓ ***Natural***
- ✓ ***Renewable***
- ✓ ***Biodegradable***
- ✓ ***Versatile***
- ✓ ***Big volumes***

(UK import = 1Mt/year)

BUT

Growth of palm oil plantations causing orang-utans' decline

5,000 orang-utans perishing every year!

Better to use Waste biomass:

There is a lot of (renewable) food supply chain waste

U.S.A.
- Whey 43,091,275 T/yr
- Corn stover 80–100 million T/yr (dry basis)

California:
- Vegetable crop residue 1 million T/yr (dry basis)
- Tomato pomace 60,000 T/yr (dry basis)
- Nut shells & pits 40,000 T/yr
- Meat processing waste 65,000 T/yr (dry basis)
- Food scraps in MSW 1.6-2 million T/yr (dry basis)

E.U.
- Starch 8 million T/yr
- Tomato pomace 4 million T/yr
- Post manufacturing food waste 34 million T/yr
- Used cooking oil 0.7-1 million T/yr
- Surplus whey 13,462 T/yr
- Surplus wheat straw 5.7 million T/yr (**UK**)
- Bread surplus 680,000 T/yr (**UK**)
- Citrus waste 0.6 million T/yr (**Spain**)

MEDITERRANEAN BASIN
- Olive mill residue 30 million T/yr

WORLD
- Rice husks 110 million T/yr
- Citrus peel residue 15.6 million T/yr
- Apple pomace 3-4.2 million T/yr
- Grape pomace 5-9 million T/yr
- Banana peels 9 million T/yr
- Kiwi residue 0.3 million T/yr

ASIA
- Palm oil 15.8 million T/yr (**Indonesia**)
- Food waste 1.2 million T/yr (**Hong Kong**)
- 25 millon T rice straw burned in open fields (**Vietnam**)

BRAZIL
- Sugar cane bagasse 376.5 million T/yr
- Corn residue 41.7 million T/yr
- Cassava residue 51.6 million T/yr
- Rice straw 4.5 million T/yr
- Wheat straw 5.4 million T/yr
- Citrus residues 9.4 million T/yr

AFRICA
- Citrus waste 139,724 T/yr (**South Africa**)
- Cocoa pods 20 million T/yr (**Ivory Coast**)
- Cashew Shell Nut Liquid 20,000 T/yr (**Tanzania**)

3? bn MT inedible FSCW waste to valorise!!

Energy and Environmental Science, 2013, 426-464.

We need more and better Green Chemical Technologies applied to real world waste problems turning them into resource opportunities

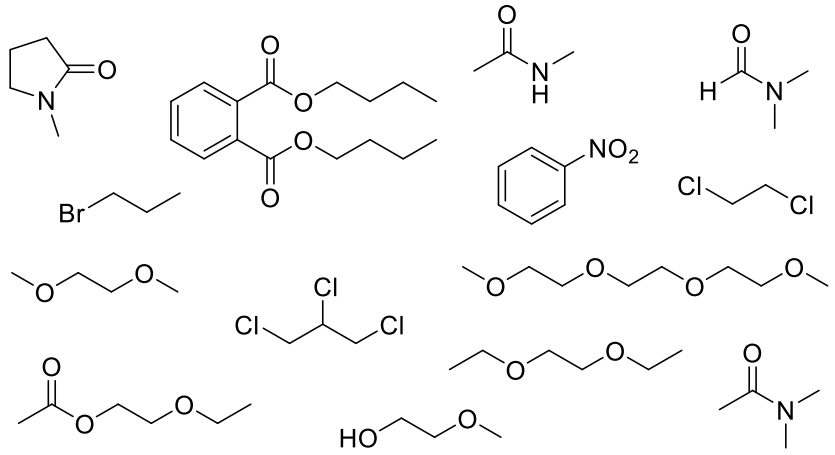
REACH

Regulation (EC 1907/2006)

Substances of Very High Concern (SVHC) include many traditional solvents

Addible.

Solutions to Complex Waste



And the list keeps growing.....

New green solvents and many other green chemicals are needed!!

SSbD – the European goal

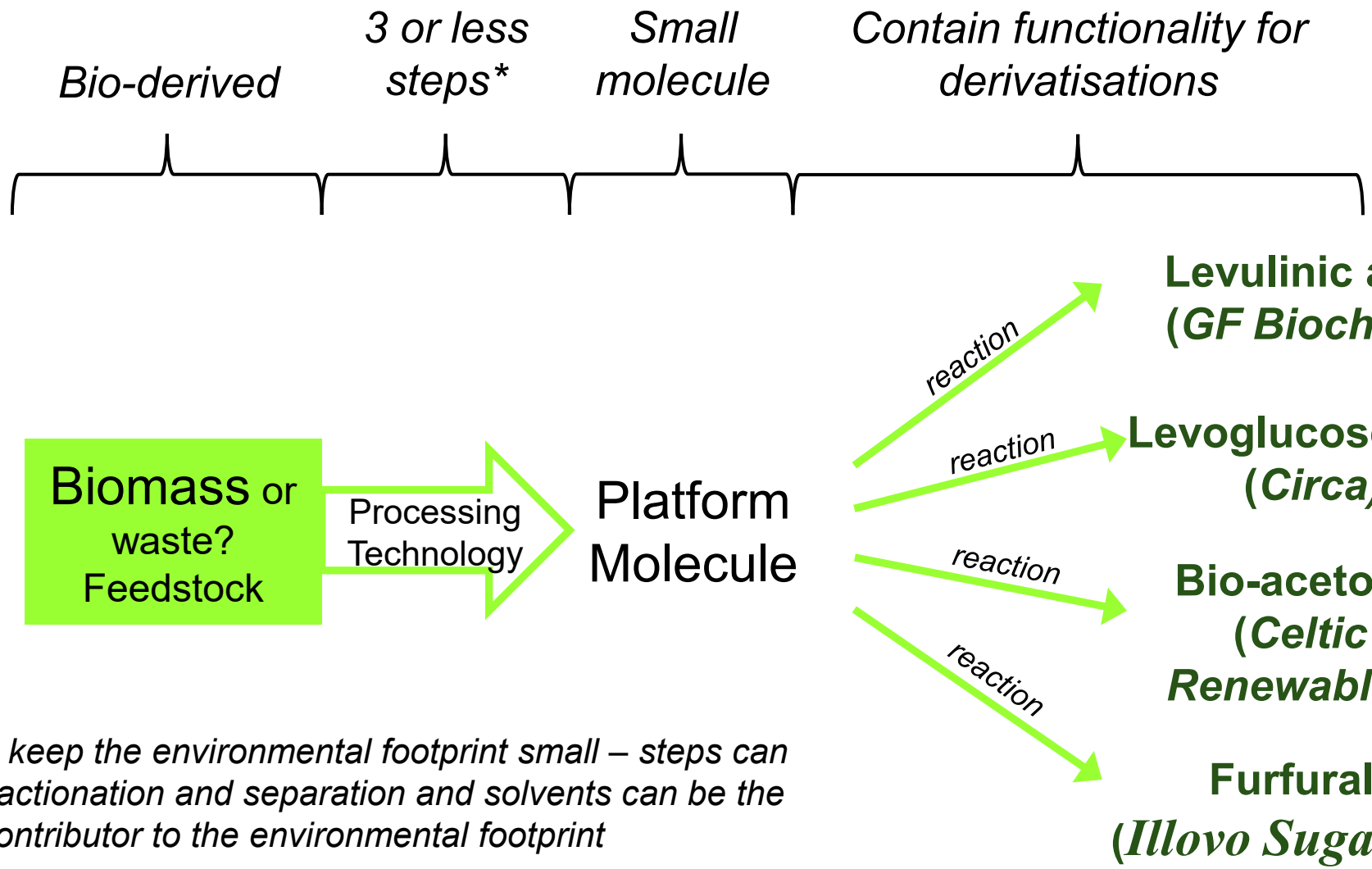
Part of the European Green Deal objectives:

- all chemicals must be used safely and sustainably
- substance of concern must be substituted and minimized
- the most harmful chemicals should be avoided

Producers should consider the above at the design stage of a new product

- good for human health
- future proofing the business

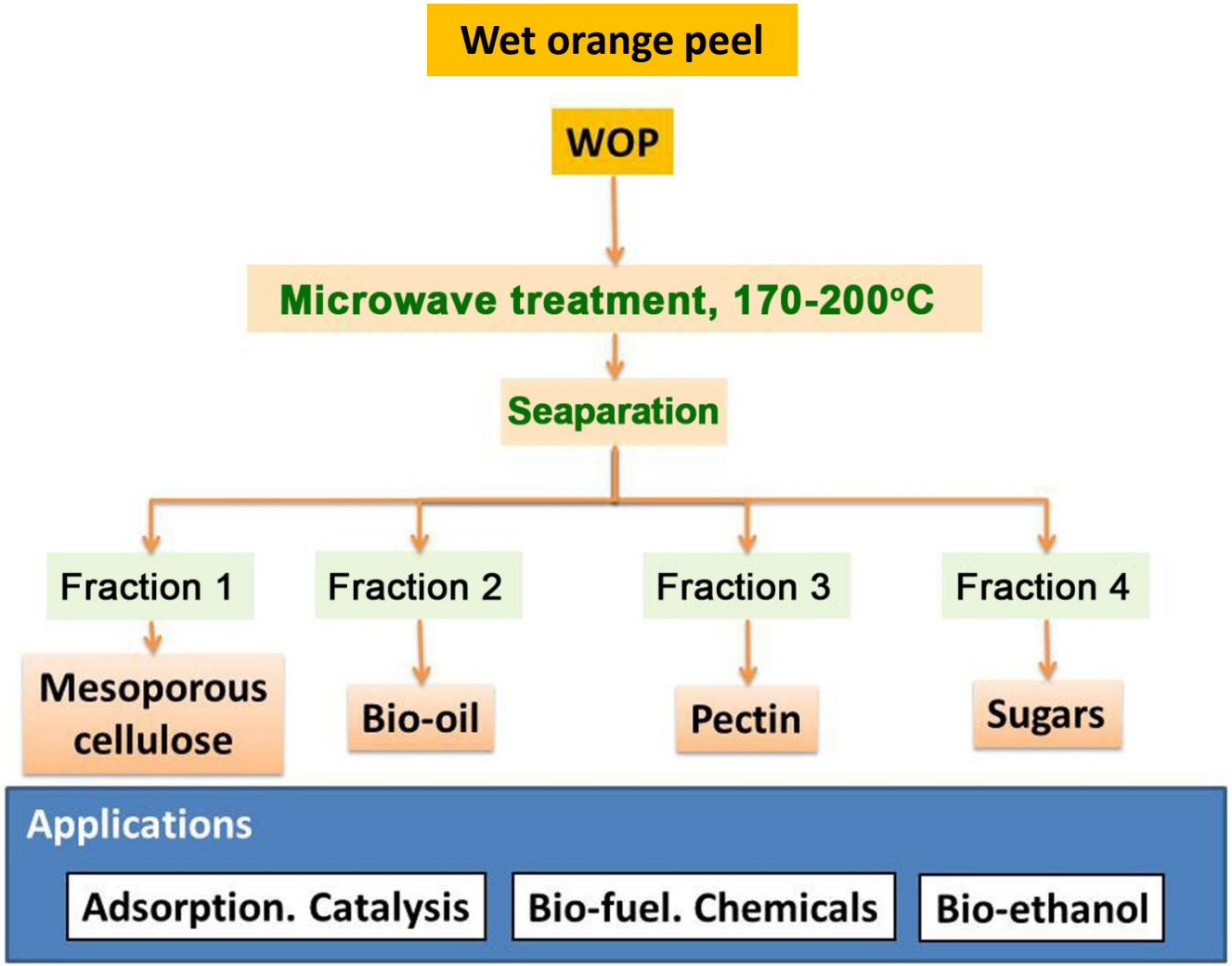
Bio-based molecules can be the future but they need to be green across their lifecycle



*we must keep the environmental footprint small – steps can include fractionation and separation and solvents can be the biggest contributor to the environmental footprint

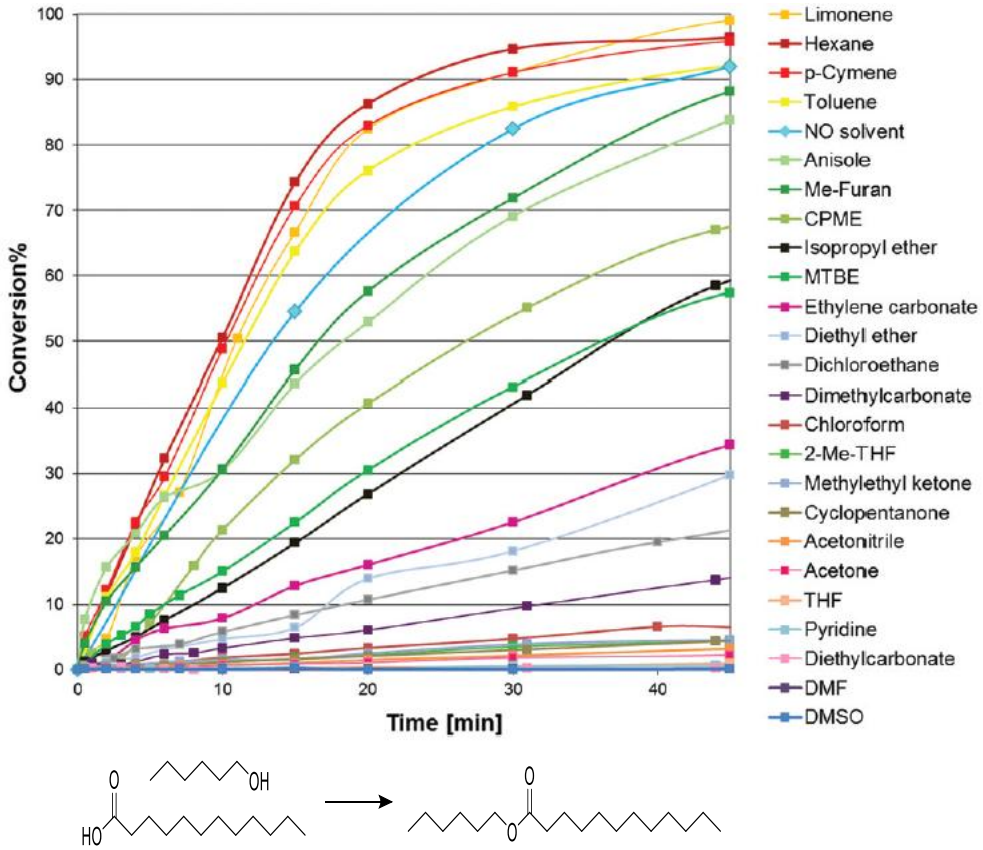
One example.....from bio-waste to solvent (++) using a green chemical technology ....early commercialisation

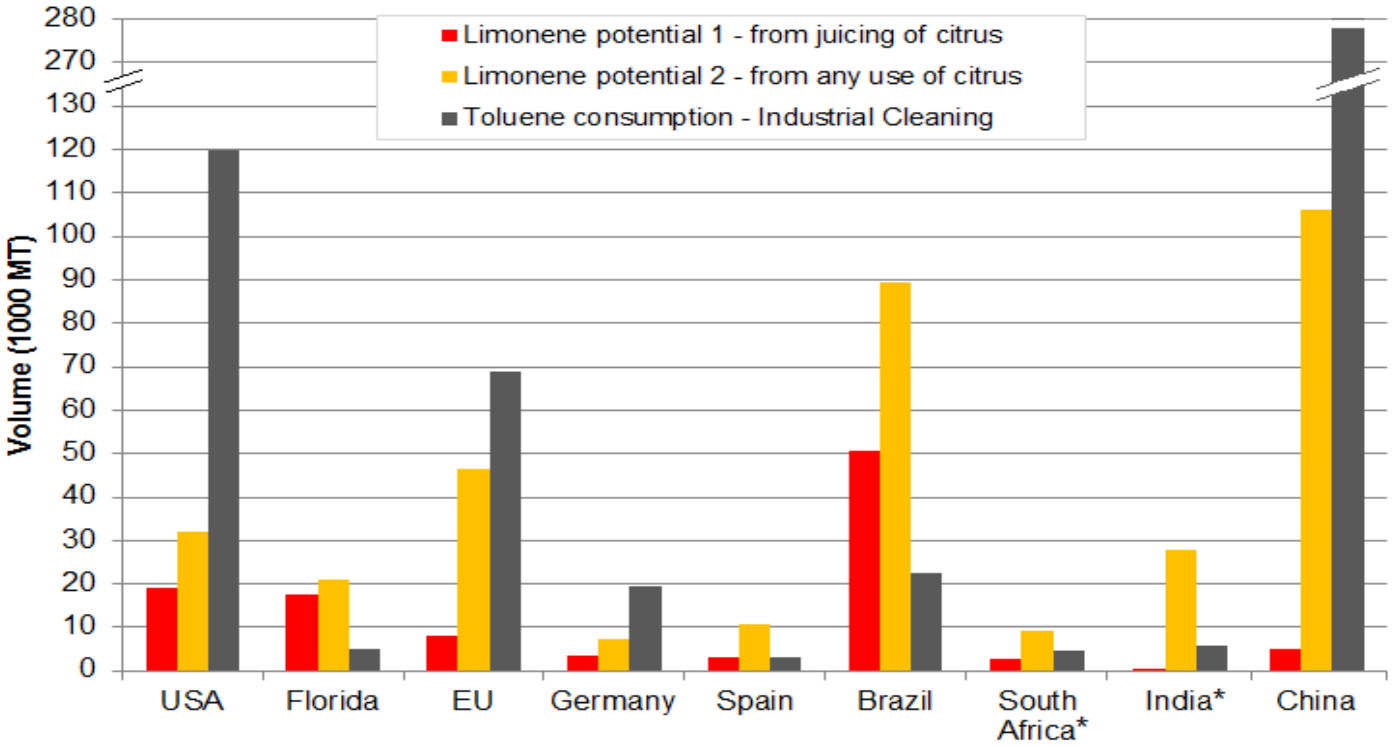
MW Bio-refinery of Orange Peel



Including Limonene

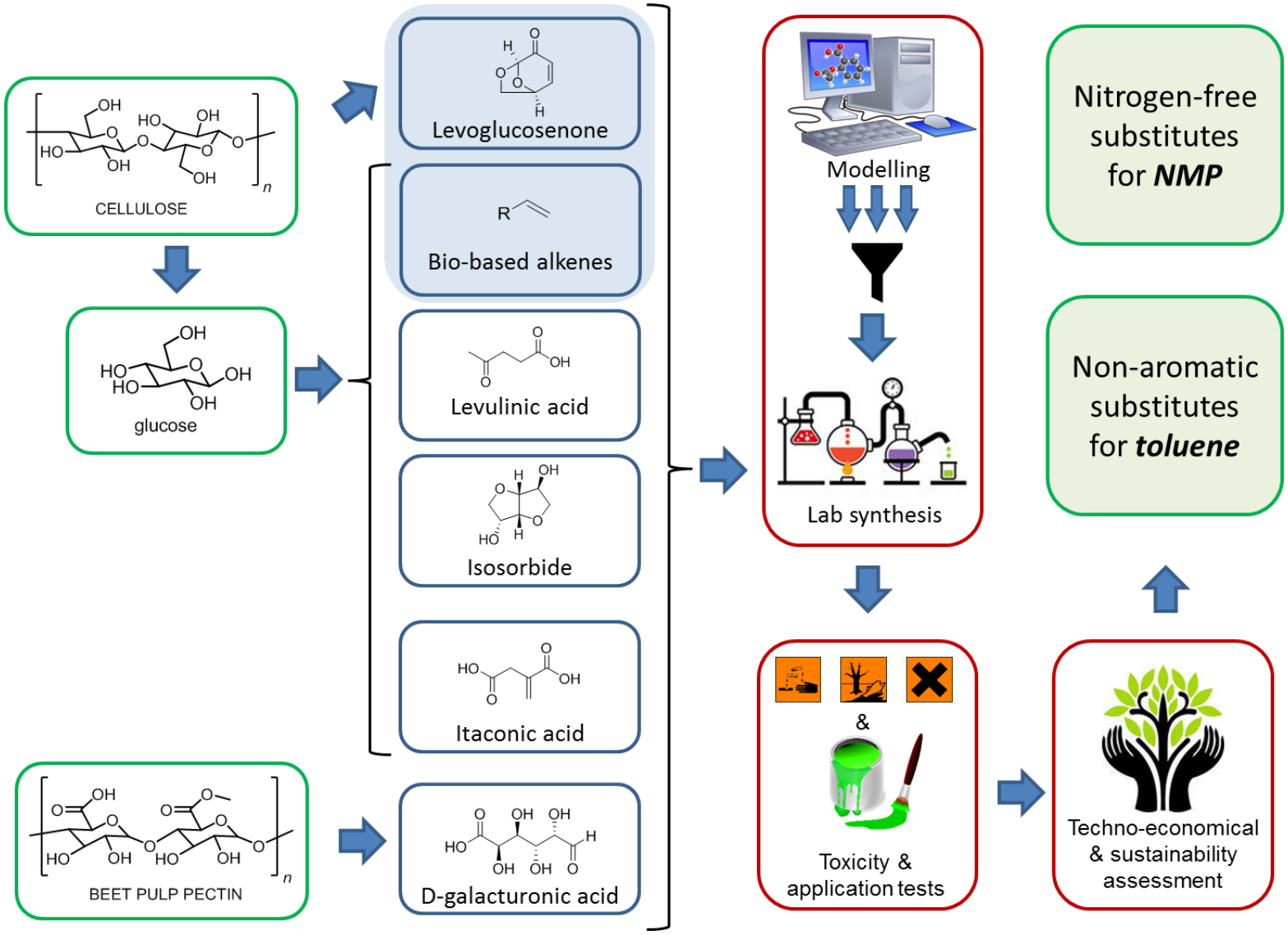
Limonene can make a difference in the huge solvents market but only in some regions





We need to use green chemistry to make new *genuinely green and sustainable* (and cost-effective) solvents

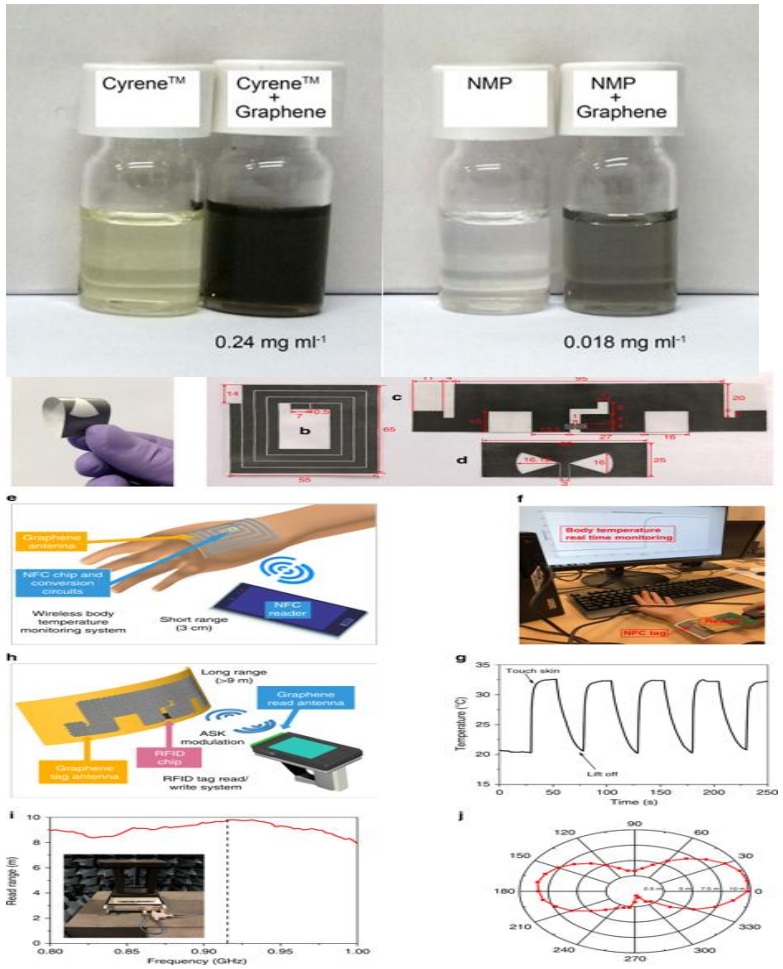
EU BBI Project RESOLVE – the emergence of greener solvents

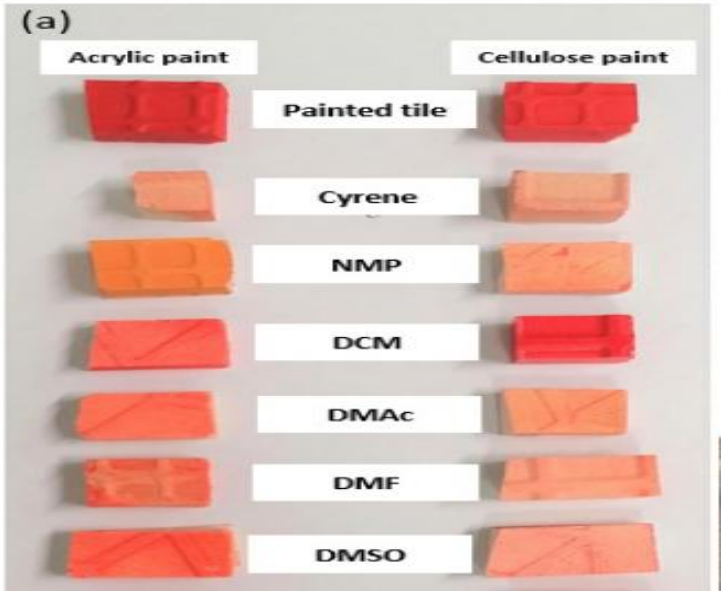


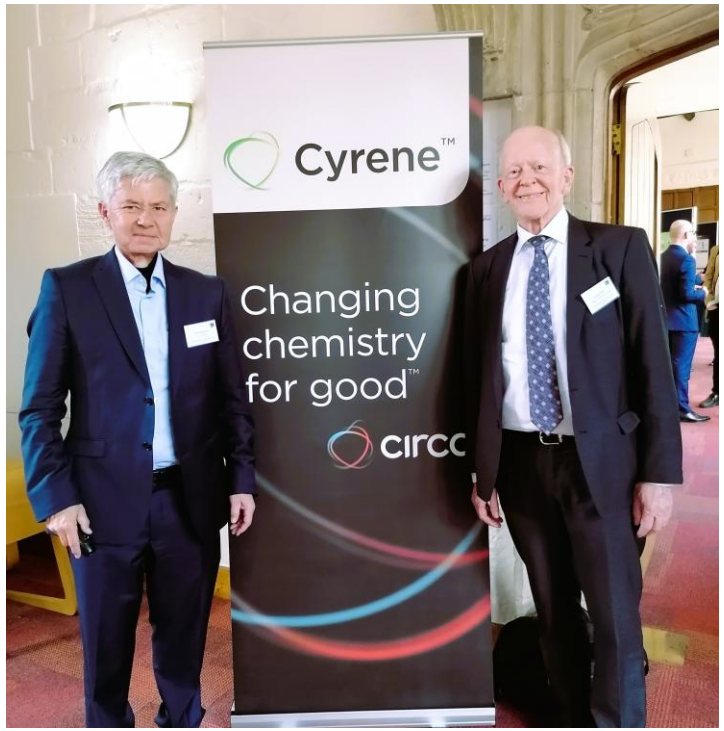
cyrene®

A ***bio-based*** *alternative for dipolar aprotic solvents*

Proven in graphene production, cleaning and many other applications







Royal Society of Chemistry announces the **2025 Team Award Prize** for proving the diversity in application of the new green and safe solvent Cyrene™ invented by Clark

And manufactured at multi-T scale BUT.....

TMO - a green replacement for toluene

Properties

- Bp: 112 °C
- Mp: <-90 °C
- Density: 0.802 g ml^{-1}

2,2,5,5-Tetramethyloxolane
2,2,5,5-Tetramethyltetrahydrofuran
CAS: 15045-43-9
SMILES: CC1(CCC(O1)(C)C)C

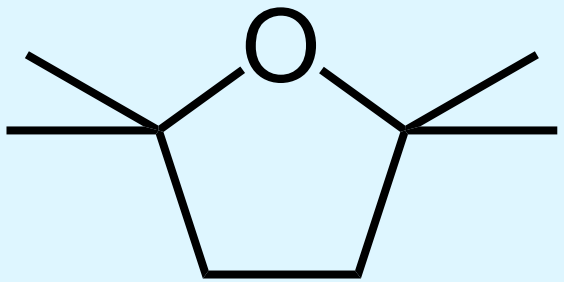
Immiscible with water

- 6 ppm water content after drying with molecular sieves
- 8,737 ppm water content when saturated

Addible.
Solutions to Complex Waste

Proven Applications

- Radical-initiated polymerisation
- PSA coating
- Solid-phase peptide synthesis
- Mitsonobu reaction
- Grignard reaction
- Enzymatic polycondensation
- Buchwald-Hartwig amination



Non-polar solvent

HSP: δ_D: 15.6; δ_P: 2.3; δ_H: 2.4

KAT: α : 0.00; β : 0.70; π*: 0.30

Log $K_{(o/w)}$: 2.40

Low-toxicity

- Integrated *in silico – in vitro* tox screening
- Tested on multiple tox endpoints
- No indication of CMR toxicity

Safe

- Non-peroxide forming ether
- No inhibitor required
- Autoignition temperature: 417 °C
- LEL: 0.9%

Can it make the transition to a large volume (commodity) solvent?

TMO2 – Novel Oxidant

Chemistry World, 5 February 2026

Reinventing Oxidation: Simpler, safer, smarter

TMO_2 is a novel, peroxide based reagent for efficient, non-aqueous oxidation reactions… an organic source of hydrogen peroxide!

1. **ReSolve project**
2. **TMO foundation**
3. **TMO_2 development**
4. **Real world applications**

Building on TMO, one of ReSolve's target solvents, the Addible team has independently developed TMO_2 as a greener, non-aqueous, stable, hydrogen peroxide reagent in an organic solvent.

Rubber Recycling
Enables efficient devulcanization of mixed rubber waste

Chemical Synthesis
Used in chemical synthesis to create new chemicals

Textile recycling
Innovative recycling routes in cellulose rich fabric materials

Seeking collaborators to test TMO_2 in oxidation, synthesis and recycling applications… get in touch at contact@addible.eu

addible.eu/tmo2

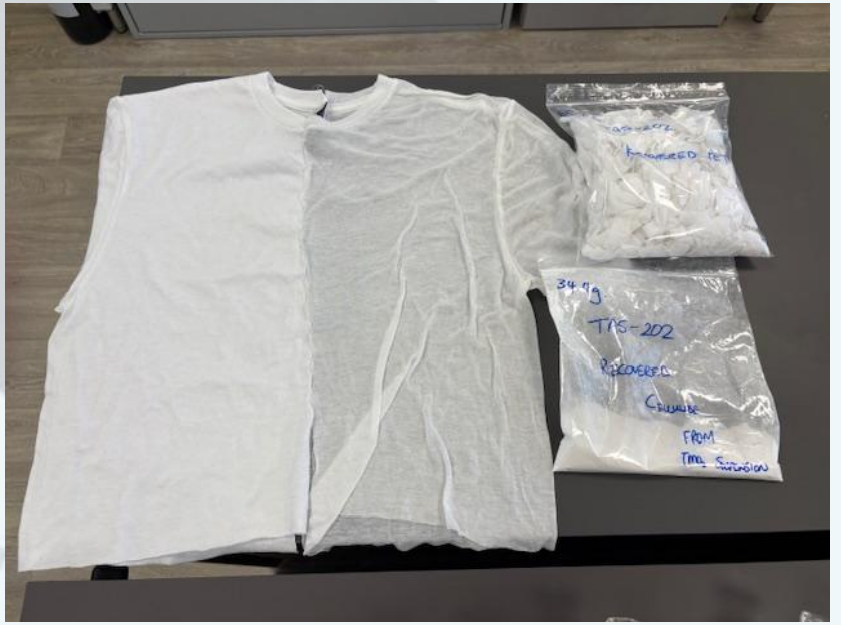
Oxycycle technology – combining a green solvent and a green reagent

Recycling a complex waste - Polycotton

- After filtering we are left with ‘clean’ recovered PET and cellulose
- Total mass recovery (large scale, polycotton (40:60-PET:cotton) 92%
- Clean PET 46%
- Clean cellulose 46%
- Large scale process is currently being optimised

Clean PET

Clean Cellulose



Before Polycotton ***After Clean PET***

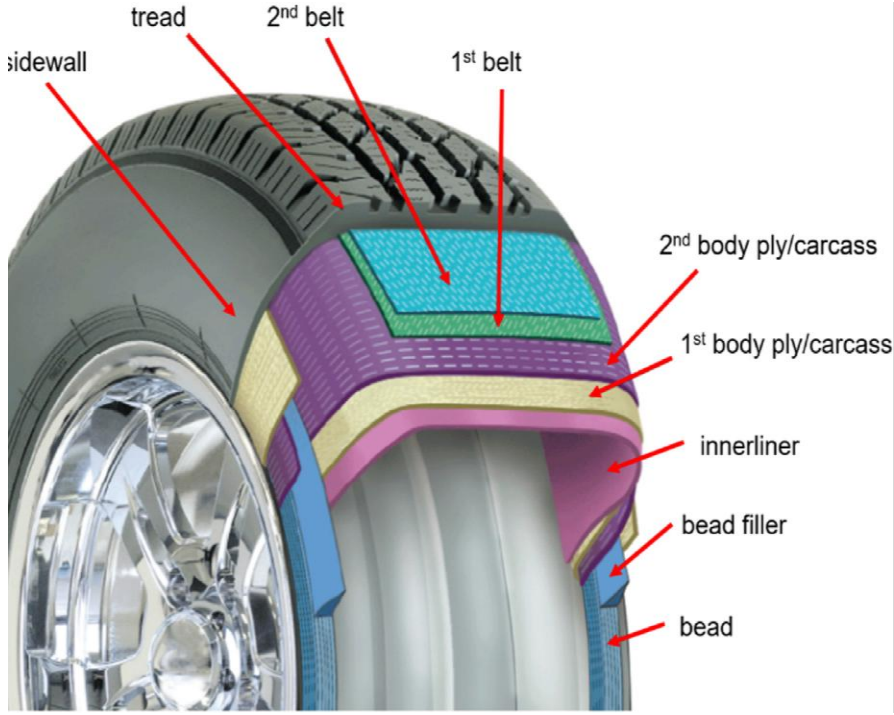
Tyres are very complicated and a great opportunity!

Tyre mountains visible from space!

I bn tyres a year

<10% recycled.....Enormous waste problem but also a great resource opportunity

Composition	Car tyre	Truck tyre
Natural rubber	14%	27%
Synthetic rubber	27%	14%
Carbon black	28%	28%
Steel	14%	14%
Textiles, fillers, accelerators, antiozonants, etc	17%	17%
Estimated average weight	9-11 kg	45-54 kg



Addible's OxyCycle Process

OxyCycle converts end-of-life tyres into high-value circular materials — Closing the loop on one of the world's toughest waste streams

Pre-wash
- TMO removes additives (~10% wt)
- Delaminates rubber layers

→

Devulcanise
- TMO_2 breaks S–S bonds under mild conditions

→

Separate
- Filter carbon black, metals & textiles

→

Wash & Recover
- Water removes sulphur compounds, recycle reagent

Waste tyre

Tread | Sidewall | Inner liner

Waste (i.e. t

Clean Textiles lon)

ChemComm

COMMUNICATION

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TMO_2 – a novel non-aqueous source of hydrogen peroxide

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rsc.li/chemcomm

Oxidation is a linchpin of the chemical industry, used in the manufacture of ~60% of all products and intermediates with an associated global value estimated at USD 20–40 billion. Hydrogen peroxide (H_2O_2) is the preferred green oxidant by virtue of outstanding atom economy and benign co-product (water), yet its routine delivery as dilute aqueous solutions imposes water-compatibility constraints, biphasic mass-transfer penalties, waste generation and costly separations. We report TMO_2, a non-aqueous, bench-stable source of H_2O_2 formed in the green, reusable solvent TMO, decoupling oxidant delivery from water. TMO_2 enables peroxide oxidations under homogeneous, organic conditions, obviating phase-transfer operations and reducing waste while avoiding hazardous peracids (Addible Ltd., TMO_2 International Patent Application No. PCT/EP2025/074472). Concept, preparation, and representative reactivity are described herein; full procedures and data are provided in the SI.

Oxidation reactions are arguably the most pervasive class of transformations in chemistry.[1] They are involved in the manufacture of ~60% of chemicals and intermediates, corresponding to a global commercial value in the order of USD 20–40 billion.[2] Beyond synthesis, oxidation supports numerous waste-treatment and valorisation systems. As such, a long-standing goal has been to couple the importance of oxidation with safer, cleaner reagents and operations. Hydrogen peroxide (H_2O_2) has emerged as the oxidant of choice for this purpose, offering exceptional atom efficiency relative to alternatives and producing only water as stoichiometric by-product.[3] Global H_2O_2 output exceeds 4 million tonnes per year sustaining applications from bleaching and sterilisation to high-volume syntheses (e.g., caprolactam, propylene oxide).[4,5] Future important applications are likely to include oxidative upgrading of organic wastes, including polymers and end-of-life tyres where hydrogen peroxide would be preferred to more hazardous peracids.[6] However, the use of normal aqueous H_2O_2 is often problematic due to immiscibility or water sensitivity of substrates necessitating biphasic operations with halogenated solvents and phase-transfer catalysis, as well as transition-metal salts meaning multiple unit operations and waste-intensive downstream separations. Concentrated solutions can evolve O_2, heightening flammability risks in organic media, consequently, large excesses are routinely charged to offset decomposition.[7] These practicalities erode the intrinsic "greenness" of peroxide oxidation. Beyond the oxidant itself, the solvent environment is pivotal. In the drive towards greener chemistry, 2,2,5,5-tetramethyloxolane (TMO) has been identified as among the greenest and most sustainable solvents, outperforming widely used media such as tetrahydrofuran, 2-methyltetrahydrofuran, toluene, and dichloromethane.[8] Yet even in green solvents, many peroxide-based systems remain encumbered by complexity, for example, the classic Noyori biphasic oxidation of sulfides requires a multi-component mixture complicating scale-up and limiting adoption.[9] Solid adducts such as urea–hydrogen peroxide (UHP) avoid water but suffer reduced reactivity and atom economy while generating urea waste streams, limiting adoption in synthesis.[10] Organic peracids operate anhydrously yet are costly, produce stoichiometric carboxylates, and pose handling and transport hazards (e.g., peracetic acid).[11] A non-aqueous, operationally simple, and safer peroxide source is therefore needed. Herein we introduce TMO_2 – hydrogen peroxide captured within TMO, a non-toxic, stable, and recyclable solvent – providing anhydrous delivery of H_2O_2 without peracids or phase-transfer scaffolding. TMO_2 is bench-stable and easy to dispense, enabling homogeneous peroxide oxidations in common organic media (Fig. 1). We have previously introduced 2,2,5,5-tetramethyloxolane (TMO) as a green, low-polarity, non-toxic ether solvent.[12] A defining advantage of TMO over conventional ethers is its exceptional resistance to autoxidation, maintained even under forcing conditions. The α,α′-disubstitution removes α-C–H bonds adjacent to oxygen and sterically shields the ring

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TMO

TMO for regeneration to TMO_2

TMO_2

***Addible: Chem. Commun.*, 2025**

Why OxyCycle is different

- ✓ Achieves **true circularity** with high-value recovered materials, upcycling only!
- ✓ Operates under TMO_2: a **mild, bio-based oxidant**
- ✓ **Selectivity to sulphur bonds** but preserves C=C integrity
- ✓ Delivers **~98%** overall material recovery **efficiency**
- ✓ Reuses its TMO_2 chemistry in a **closed loop**
- ✓ Produces **clean carbon black** ready for reuse
- ✓ Protected by a **patent pending** green oxidation process

Tyrefinery? ™

- A model for a truly circular economy

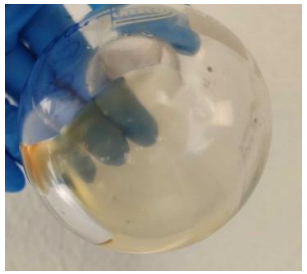
Ibn tyres pa + xbn stockpiled
(many locations)

And many other
Rubber wastes

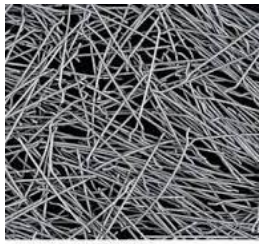
Mechanical Pre-treatment

Rubber crumb

OXYCYCLE technology



Rubber
(tyres, coatings)



Steel and other

Chemicals including
plasticers

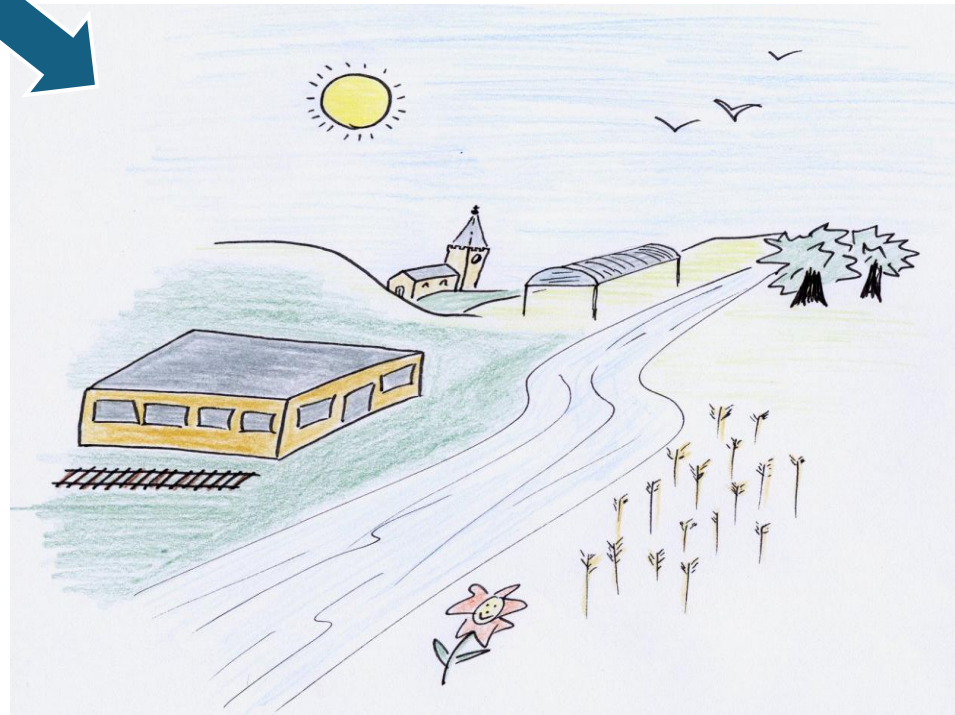
Carbon black
Batteries, new tyres..

Textile fibers (Teijin))

From the old to the new:
A future *Sustainable* Chemical Industry

Old chemical industry

New green chemical industry



TRANS PHARM

Thank you