Future prospects of perovskite solar cells:
Summer School in Khiva

14 – 21 May 2023

Principles of Materials Circular Economy

Rajan Jose

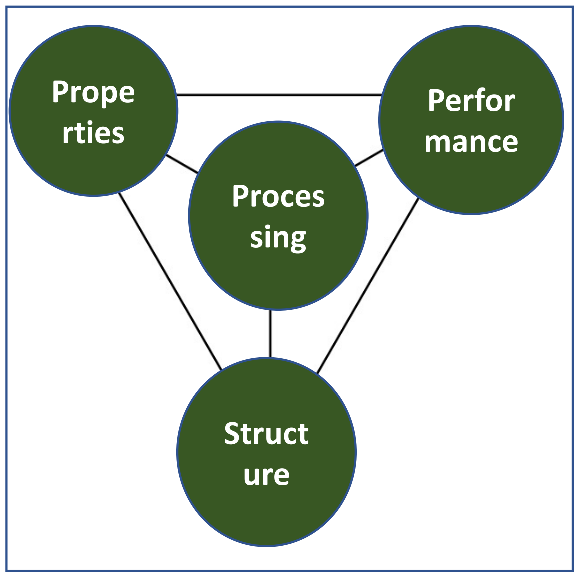
Faculty of Industrial Sciences & Technology

Universiti Malaysia Pahang

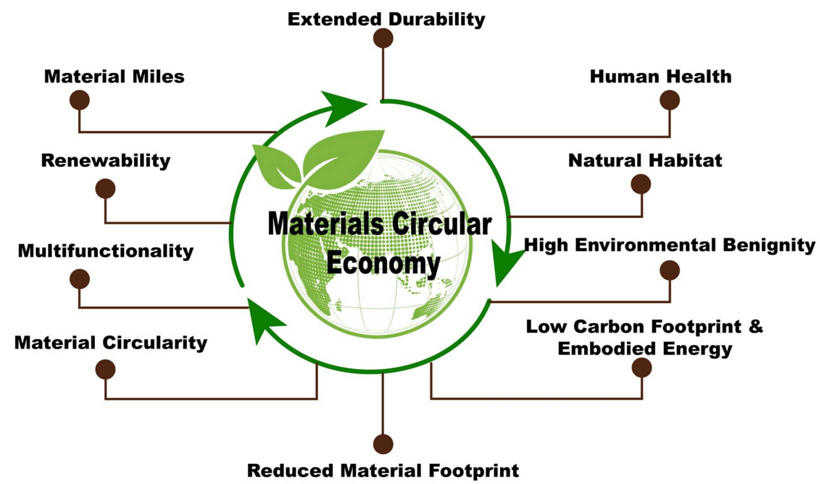
rjose@ump.edu.my

Materials: Primary contributor to the economy & quality of life

Materials Circular Economy fosters a healthy living via sustainable resourcing, processing & use of materials.

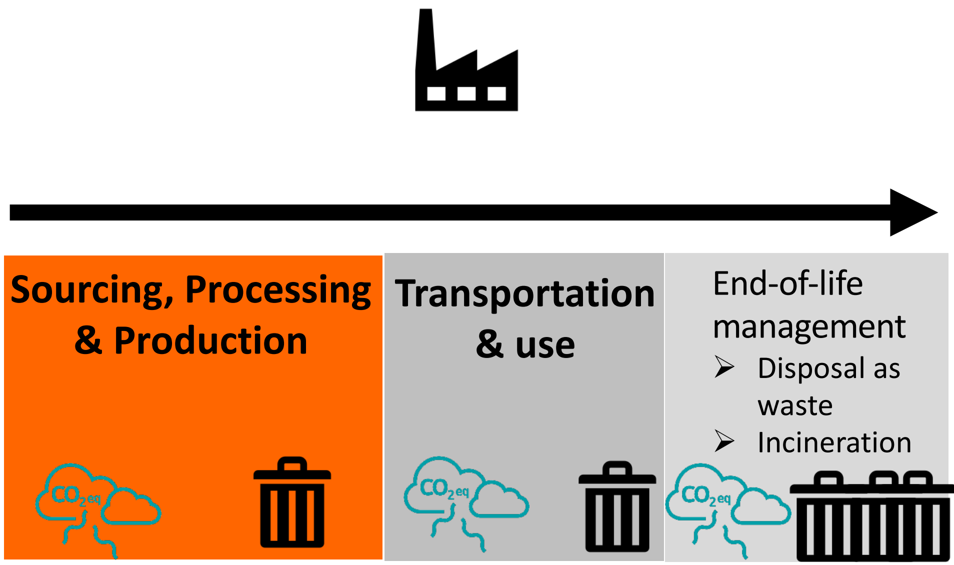


Old paradigm



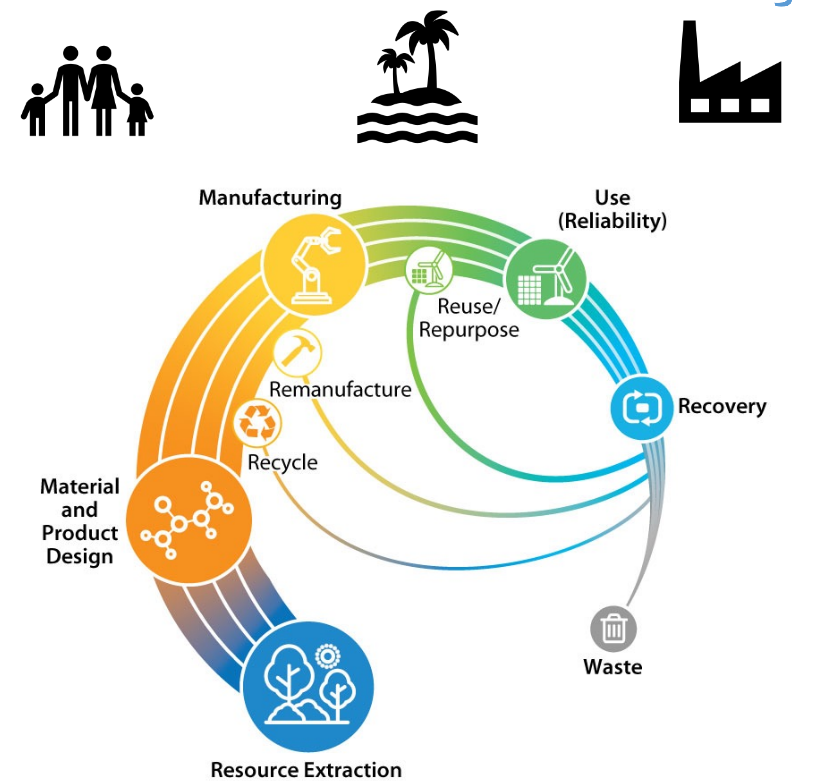
Emerging paradigm

Linear Economy



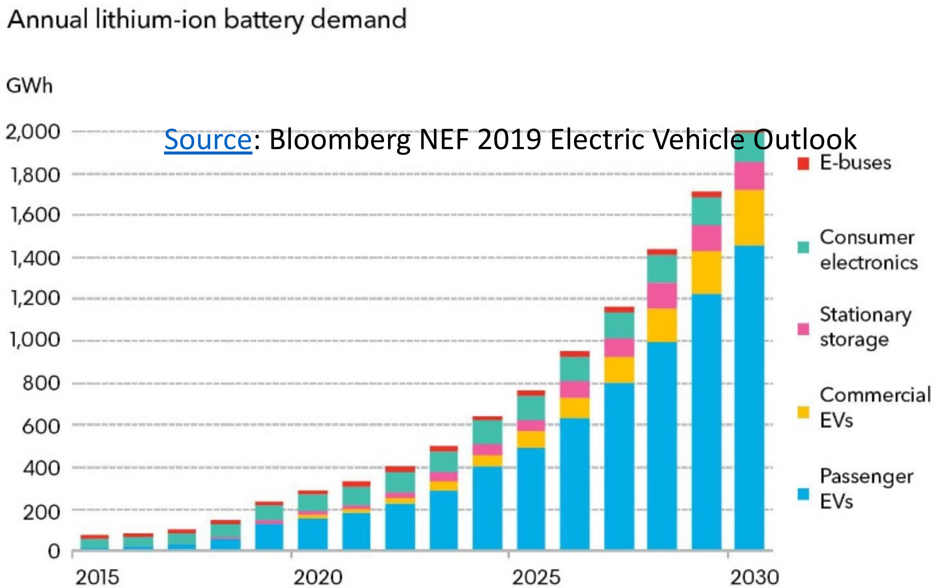
- Materials waste; energy waste; CO_2 emission leading to global warming & global waste crisis.
- Leading to depletion of natural resources.
- Toxified anthropogenic mass.

Circular Economy



- Minimising or eliminate (Materials waste; energy waste; CO_2 emission)
- Environmental, Social, Governance, and Economic benefits
- $4.5 trillion economy
- 95 million jobs (50 million in service sector & 45 million in waste management)
- Reduction of 1.5^{o}C by 2050

Electron economy, projection & consequences



Source: Bloomberg NEF 2019 Electric Vehicle Outlook

Current: NCM//$LiPF_6$//Graphite

Future: NCM//$LiPF_6$//Silicon

- 20 tonne of CO_2 per tonne of lithium.

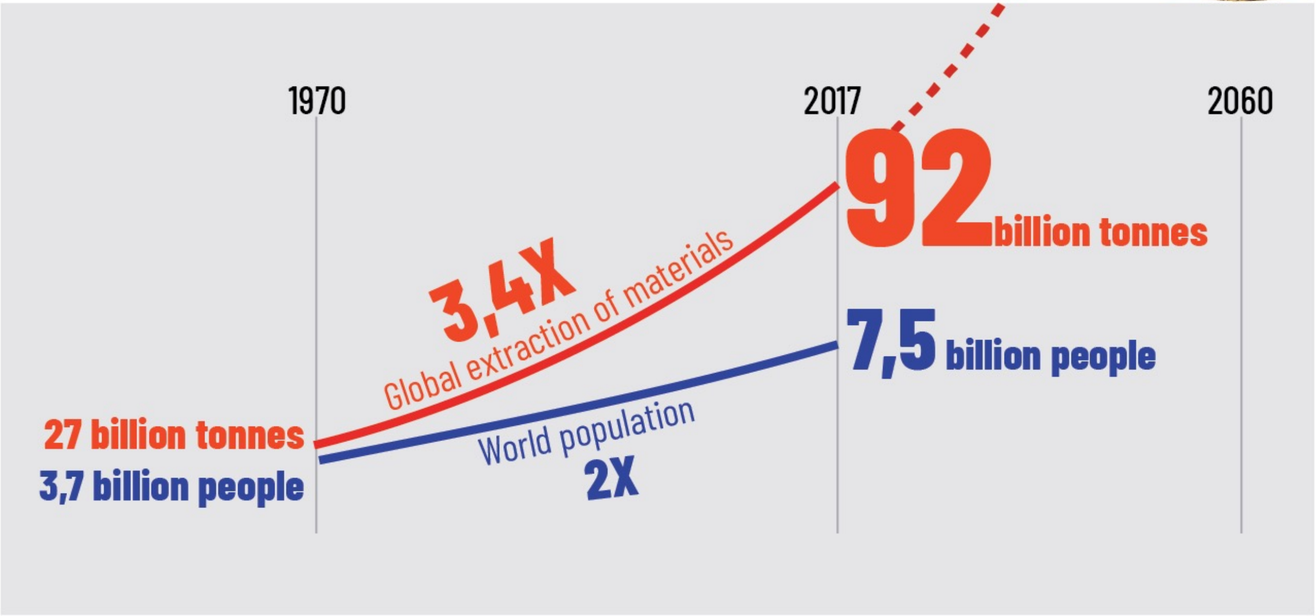
- Processing of electrode materials cause carbon emissions in the range 59-119 kg CO_2-eq/kWh battery, with a midpoint of 89 kg CO_2-eq/kWh

- Reports have shown that LiB could be recycled; the recycled batteries are on a par with the fresh batteries. Recycling may add up further CO2 per processing.

(https://www.forbes.com/sites/rrapier/2020/02/16/estimating-the-carbon-footprint-of-utility-scale-battery-storage/?sh=2acc68be7adb)

WHY TAKE ACTION

it is impossible to continue extracting as we have been doing



If we continue business as usual, we will **double** the extraction of materials[1] in 2060, **far beyond the planetary boundaries[2]**.

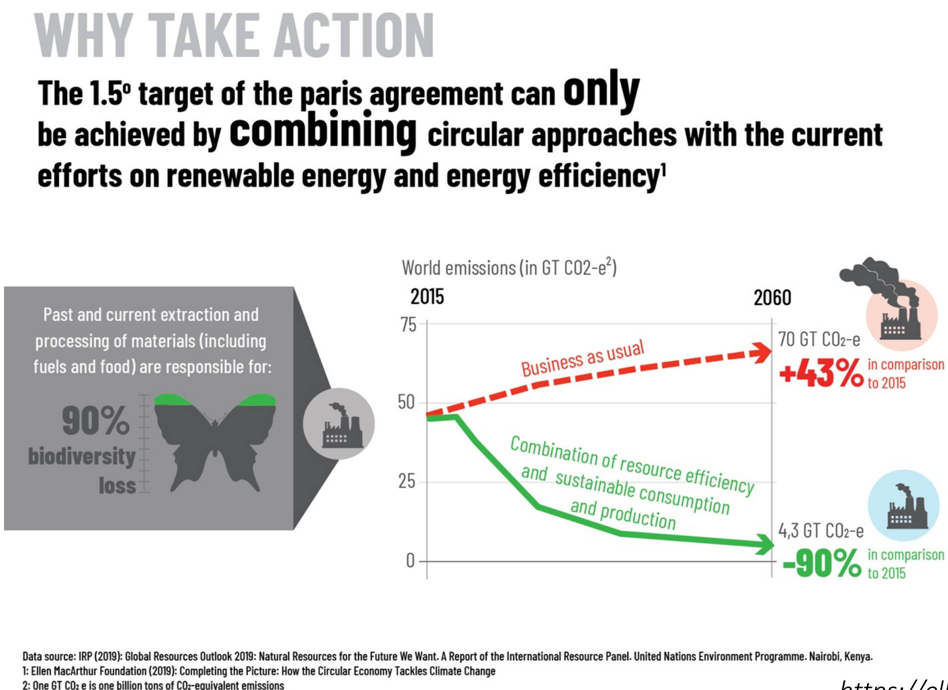
Source: IRP (2019): Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya
1: "Materials" include biomass, fossil fuels, metals and non-metallic minerals, being are a subset of natural resources which encompasses all material plus water and land.
2: For more information: https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

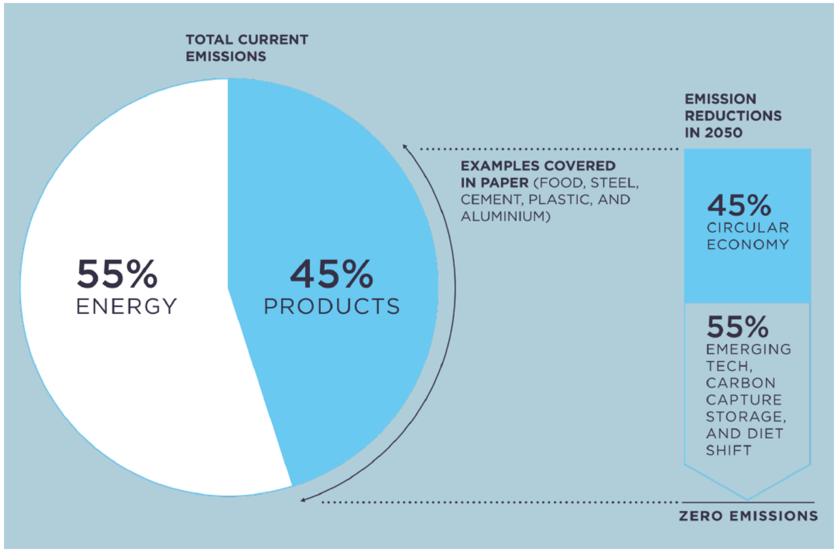
https://www.nature.com/articles/d41586-022-01508-2?WT.ec_id=NATURE-20220609&utm_source=nature_etoc&utm_medium=email&utm_campaign=20220609&sap-outbound-id=58786A23260C2F658866B7A6C74B4EC27342FFC1

https://buildingcircularity.org; https://wedocs.unep.org/20.500.11822/34184

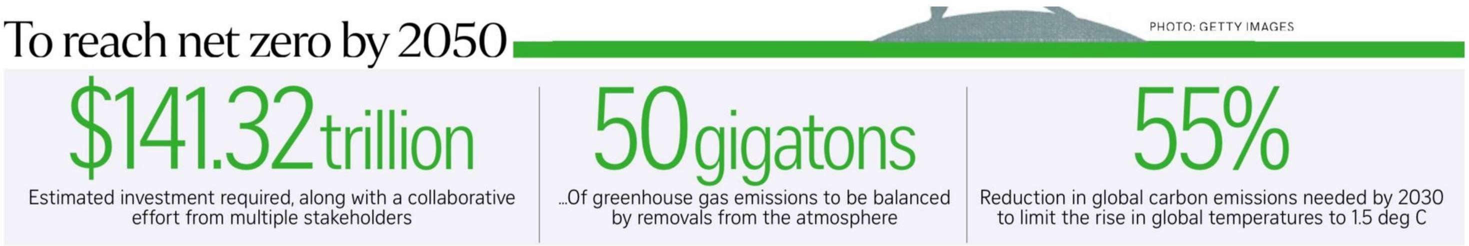
23% of global emissions are attributed to materials in 2015

- Energy efficiency and renewable energy can address 55% of global greenhouse gas (GHG) emissions.
- **The circular economy, transforming our materials and food system can help tackle the remaining 45% of emissions (22.1 BT CO2e per year).**





https://ellenmacarthurfoundation.org/articles/unlocking-the-value-of-the-circular-economy



HUMANITY'S TOP 10 EXISTENTIAL CONCERNS

Nearly a billion new consumers in every 10 – 15 years!

Materials Production
1970: 26.7 BT (~15% of total CO_2 emission)
2015: 84.4 BT (~23% of total CO_2 emission)
2050: 170 to 184BT (>30% total CO_2 emission)

- 57 Million sq. mile land in earth
- Arable <40% of total land
- Urbanization further reduce it

1. Pathogenic threats	2. Extreme weathers	3. Essentials (Food, Water, Energy, Air)	4. Sustainable Resourcing	5. Sustainable Agriculture
6. Inequality	7 Social threats	8. Human values	9. Demographic shifts	10. Mental Health

Digitally connected for 24x7 but lonely

Wealthy ~12% accounts >50% of world's emission

Endangered human rights
Geopolitical issues
Solely on amazement of wealth

Doubling of >60 years old by 2050 than 2015 (WHO)

Jose & Ramakrishna, Editorial, Mater Circ Econ 4, 26 (2022). https://doi.org/10.1007/s42824-022-00068-0

Climate change, excessive exposure to harmful chemicals & materials penalize health and social cost of humanity

1970s: 50,000 chemicals

2020s: 350,000 chemicals

Forbes

Nov 8, 2021, 06:37am EST | 947 views

Families Inhale 7,000 Microplastic Particles At Home Every Day, Reveals Study

Jamie Hailstone Contributor
Sustainability
I write about air quality and the environment.
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THE STRAITS TIMES
Tuesday, September 07, 2021

Social cost of plastic from 2019 more than India's GDP

Bags containing plastic waste dumped outside Downing Street in London by Greenpeace activists in July. PHOTO: REUTERS

Pollution, emissions, clean-up costs of plastic could be $4.96 trillion, says WWF report

MARSEILLE • The pollution, emissions and clean-up costs of plastic produced in 2019 alone could add up to US$3.7 trillion (S$4.96 trillion), according to a report released yesterday by wildlife charity WWF, warning of the environmental and economic burden of this "seemingly cheap" material.

There is increasing international alarm over the huge volumes of fossil-fuel based plastics entering the environment, as microplastics have infiltrated even the most remote and otherwise pristine regions of the world.

In its report, WWF said societies were "unknowingly subsidising" plastic, with their estimates for the lifetime costs of 2019 production equivalent to more than the gross domestic product (GDP) of India.

"Plastic appears to be a relatively cheap material when looking at the market price primary plastic producers pay for virgin plastic," said the report Plastics: The cost to society, environment and the economy. The report was produced for WWF by the consultancy Dalberg.

"However, this price fails to account for the full cost imposed across the plastic life cycle."

It estimated that unless there was concerted international action, a projected doubling of plastic production could see costs rocket by 2040 to US$7.1 trillion.

The analysis looked at factors including the greenhouse gas emissions in the production process, health impacts, waste management and estimates of the reduction in the economic "services" of ecosystems on land and in water.

Since the 1950s, roughly 8.3 billion tonnes of plastic have been produced, with around 60 per cent of that tossed into landfills or into the natural environment.

Tiny fragments have been discovered inside fish in the deepest recesses of the ocean and peppering Arctic sea ice.

The debris is estimated to cause the deaths of more than a million seabirds and over 100,000 marine mammals each year.

"Tragically, the plastic pollution crisis is showing no signs of slowing down, but the commitment to tackle it has reached an unprecedented level," said Mr Marco Lambertini, director-general of WWF International, in a statement.

The report comes as the International Union for the Conservation of Nature meets in the French port city of Marseille, with one motion under consideration calling for an end to plastic pollution by 2030.

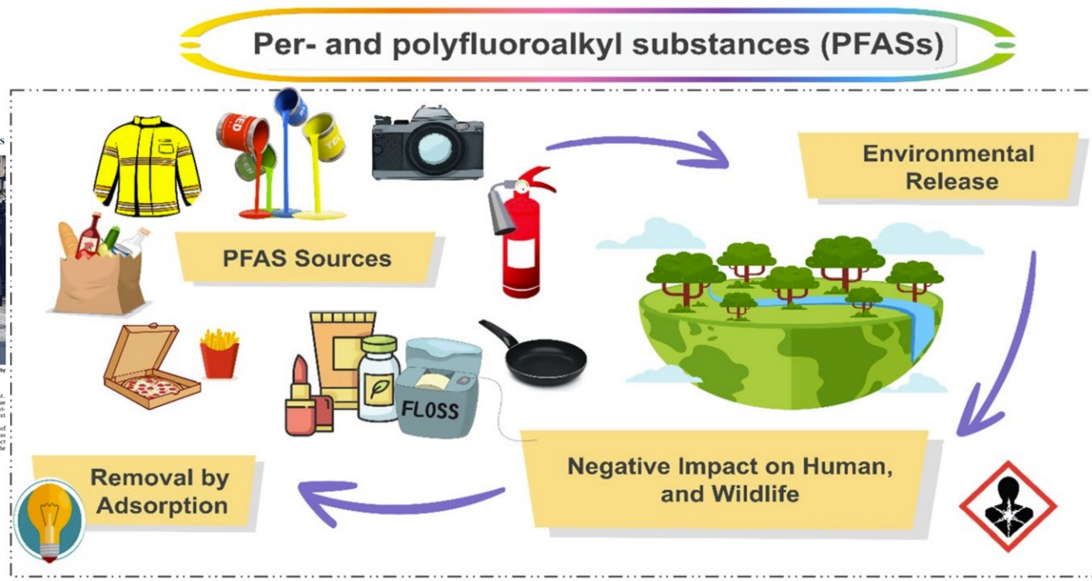
Last Thursday, the European Union threw its weight behind calls for a legally-binding international agreement to reduce plastic pollution, during talks hosted by the United Nations in Geneva.

The UN Environment Programme has said the planet is "drowning in plastic pollution", with about 300 million tonnes of plastic waste produced every year.

The proposed resolution is due to be discussed during the UN Environment Assembly in Nairobi next year.

France's minister in charge of biodiversity Berangere Abba has said that if the world failed to act there would be "more plastic in the oceans than fish" by 2050.

AGENCE FRANCE-PRESSE



THE STRAITS TIMES
Saturday, November 06, 2021

US testing lab finds cancer-causing benzene in underarm sprays

NEW HAVEN (Connecticut) • Antiperspirant and deodorant body sprays have been found to contain elevated levels of the carcinogen benzene and should be recalled, an independent testing lab said in a petition filed with the United States Food and Drug Administration (FDA) late on Wednesday.

The sprays are the latest in a string of aerosol products, including sunscreens and antifungals, that have been found to contain the cancer-causing chemical.

Earlier this year, Johnson & Johnson recalled certain aerosol sunscreen sprays under the brands Neutrogena and Aveeno. Beiersdorf recalled some Coppertone sunscreen sprays in September.

Last month, Bayer pulled certain Lotrimin and Tinactin sprays used for athlete's foot and jock itch after tests showed that some samples contained benzene.

The efforts to get the contaminated products off shelves came after Valisure, an independent testing lab in New Haven, Connecticut, alerted the FDA to its findings of benzene in suncare products in May.

Valisure followed up in recent months by testing 108 batches of antiperspirant and deodorant sprays from 30 brands and detected benzene in 59 batches at levels as much as triple the amount it found in sunscreens and detailed in the petition to the FDA.

Antiperspirant sprays from Procter & Gamble brands Old Spice and Secret contained the highest levels of benzene. An antiperspirant spray from Walmart's Equate brand and one from Unilever's Suave were also high on the list.

Most of the sprays that Valisure found to contain benzene were meant only for underarms, though the lab did find some benzene in a Victoria's Secret spray deodorant meant to be used all over the body and a Summer's Eve spray from Prestige Consumer Healthcare meant for the vaginal area.

The companies and the FDA did not immediately respond to requests for comment.

Valisure found that products that contained butane were most likely to have elevated benzene levels. Those that used alcohol as a propellant instead were least likely to be contaminated with the carcinogen.

Mr David Light, chief executive of Valisure, said he was concerned that the contamination may be coming from the raw materials companies use as propellants, such as butane and propane, which are petroleum distillates produced by refining crude oil.

"Butane is lighter fluid," Mr Light said. "Propane is the same thing you use to light your grill. These gases come out of the ground, as benzene does. Benzene is a known contaminant of these products. It seems likely these propellants are the source." BLOOMBERG

- V Menon, S Sharma, S Gupta, A Ghosal, AK Nadda, R Jose, P Sharma et al; Prevalence and implications of microplastics in potable water system: An update, Chemosphere, 137848 (2022)
- Teymourian, T., Teymoorian, T., Kowsari, E. *et al.* A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. *Res Chem Intermed* (2021).

Who we are Where we work What we do Publications & Data

16 MAY 2023 | REPORT

Turning off the Tap: How the world can end plastic pollution and create a circular economy

Authors: UNEP

This report examines the economic and business models needed to address the impacts of the plastics economy.

READ FULL REPORT

FURTHER RESOURCES

- Executive summary
- Key messages
- Topic sheet: Reuse schemes
- Topic sheet: Materials and Products substitutions
- Topic sheet: Extended Producer Responsibility
- Topic sheet: Criteria for Chemicals
- Topic sheet: Design guidelines for circularity

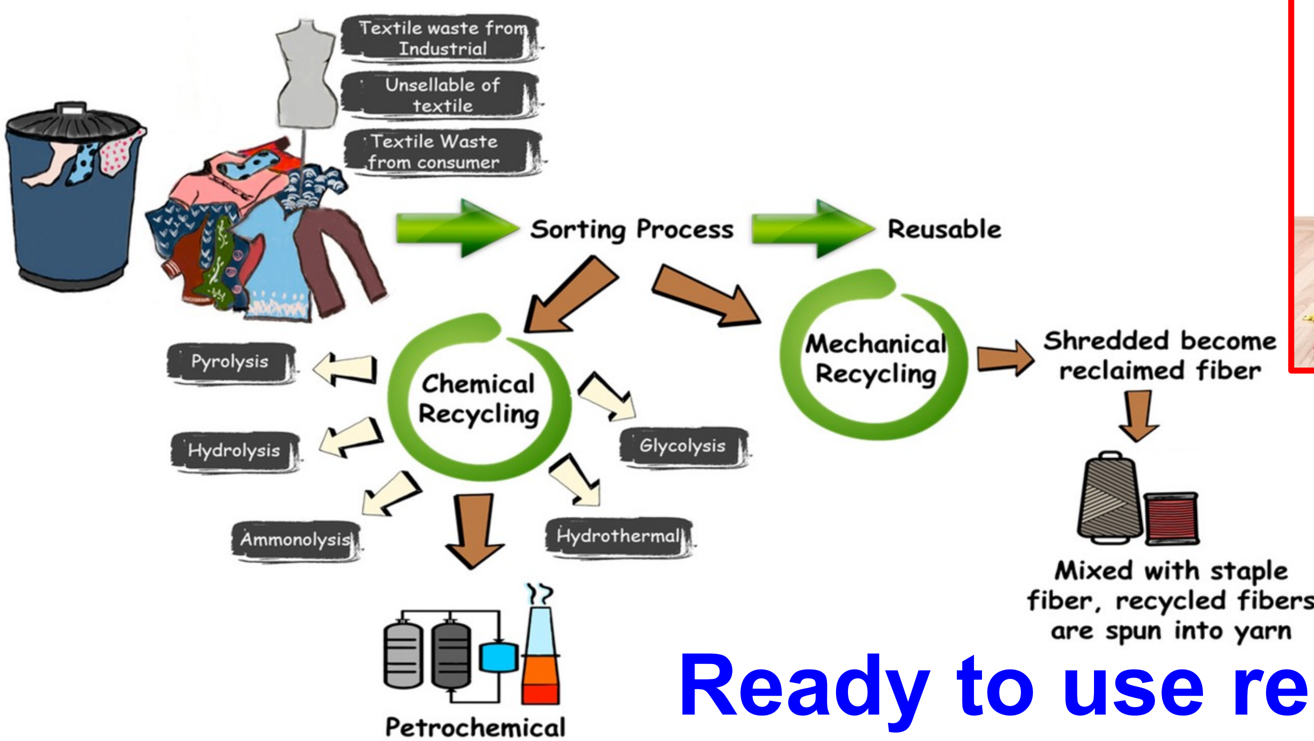
The report proposes a systems change to address the causes of plastic pollution, combining **reducing** problematic and unnecessary plastic use with a market transformation towards circularity in plastics. This can be achieved by accelerating three key shifts – **reuse, recycle**, and **reorient** and **diversify** – and actions to deal with the legacy of plastic pollution.

How concerned are we? The textile industry

Worldwide about 80 billion pieces of clothes are consumed each year

Textile mills generate **one-fifth of the world's industrial water pollution** and use 20,000 chemicals to make clothes, many of them carcinogenic. Chinese textile factories alone produce about three billion tons of soot (air pollution linked to respiratory and heart disease) every year by burning coal for energy.

A cotton bag must be used over 50 years to offset the pollution while it is made!



Ready to use recycled cloths?

The existential challenges

Nearly a billion new consumers in every 10 – 15 years!

Man-made mass exceeds living biomass

*BT – Billion Tonnes

Nature (2020). https://doi.org/10.1038/s41586-020-3010-5

Science of The Total Environment, 2022, 151208

Global warming

Waste doubles in every decades

ELSEVIER

Environment International

Volume 163, May 2022, 107199

Full length article

Discovery and quantification of plastic particl pollution in human blood

Heather A. Leslie [a], Martin J.M. van Velzen [a], Sicco H. Brandsma [a], A. Dick Vethaak [a, b], Juan J. Garcia-Vall H. Lamoree [a]

[a] Dept. of Environment and Health, Faculty of Science, Vrije Universiteit Amsterdam, De Boelelaa 1081 HZ Amsterdam, the Netherlands

[b] Deltares, Delft, the Netherlands

[c] Cancer Center Amsterdam and Amsterdam Infection and Immunity, Amsterdam University Med (VUmc location), De Boelelaan 1108, 1081 HZ Amsterdam, the Netherlands

Received 21 December 2021, Revised 11 March 2022, Accepted 18 March 2022, Available online 24 Mar Version of Record 19 April 2022.

17/22 (~80%) healthy people chosen randomly has microplastic in their blood

nature

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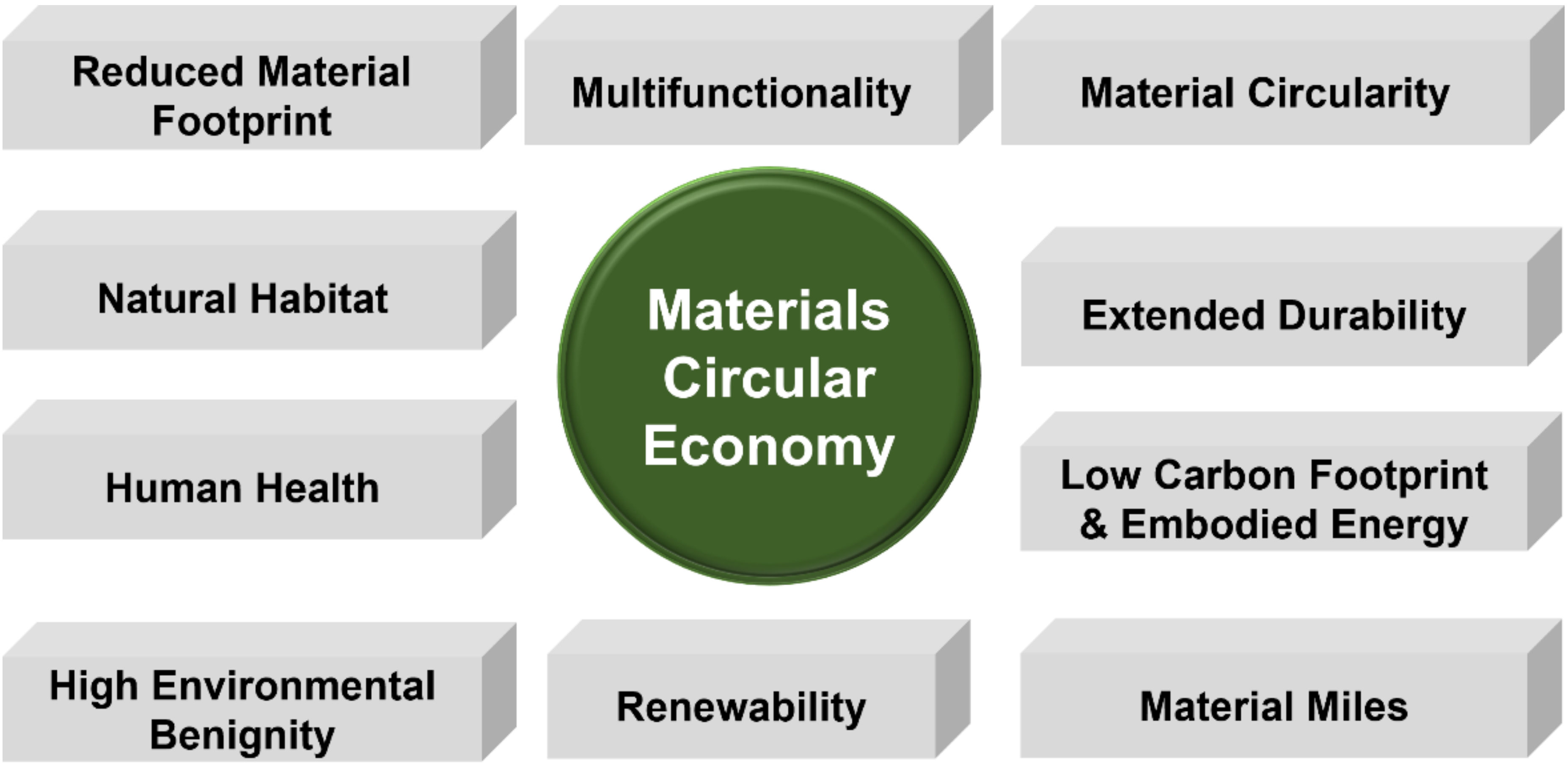
Methane is at least 28 times as potent as CO_2 for greenhouse effect

NEWS | 08 February 2022 | Correction 08 February 2022

Scientists raise alarm over 'dangerously fast' growth in atmospheric methane

As global methane concentrations soar over 1,900 parts per billion, some researchers fear that global warming itself is behind the rapid rise.

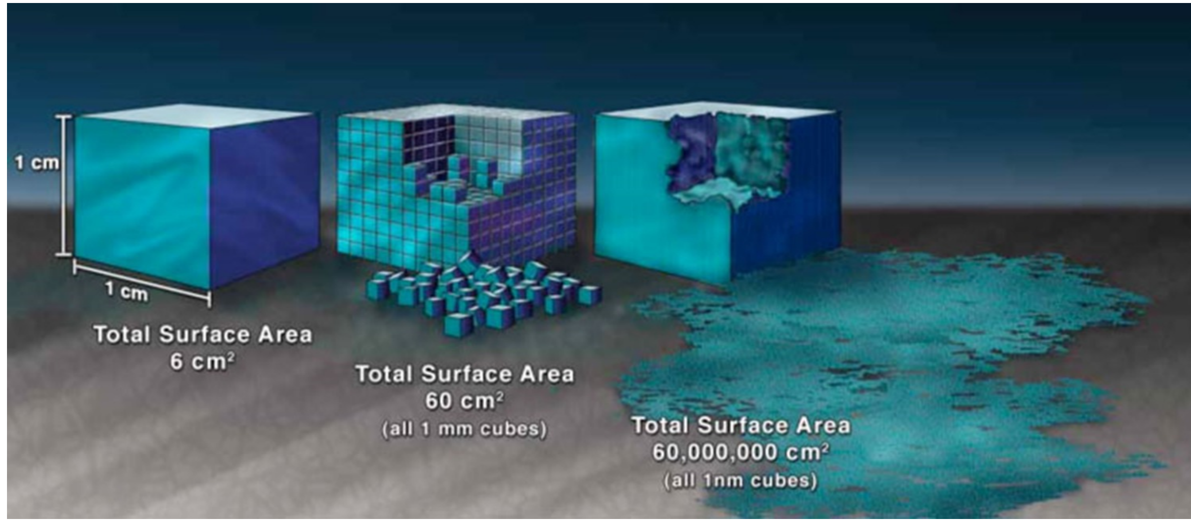
Principles of Materials Circular Economy

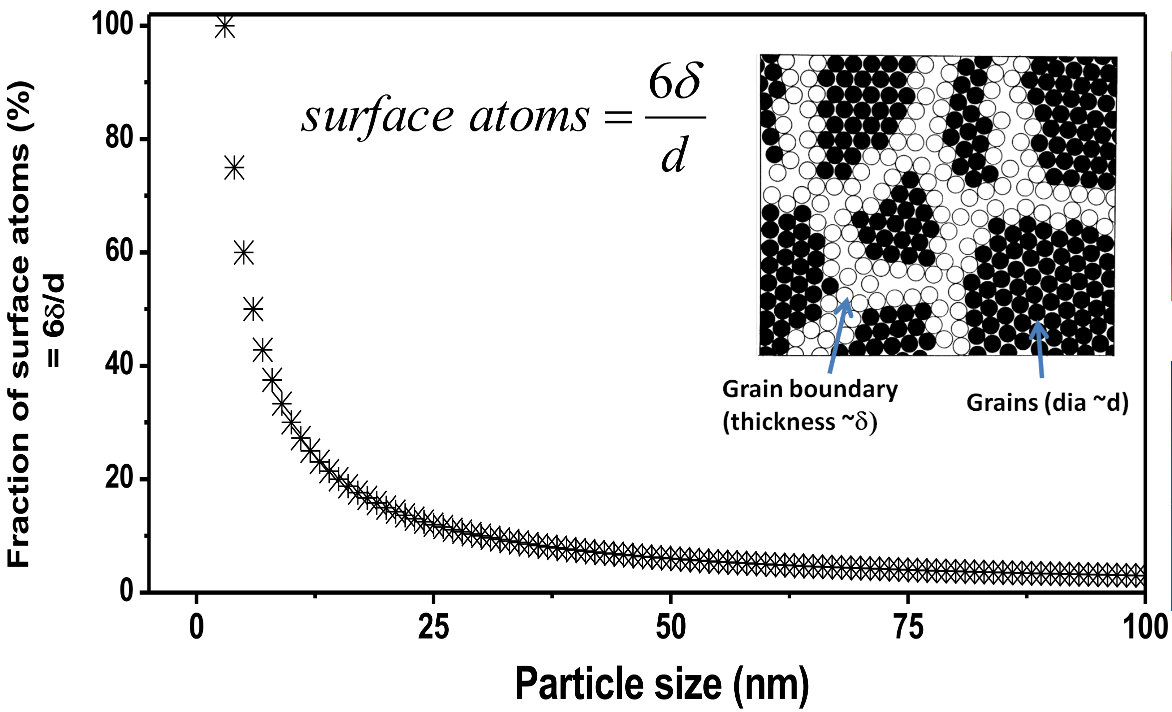


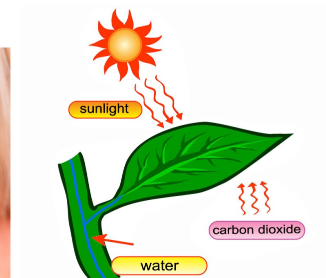
Matter 5 (12), 4097-4099 (2022)

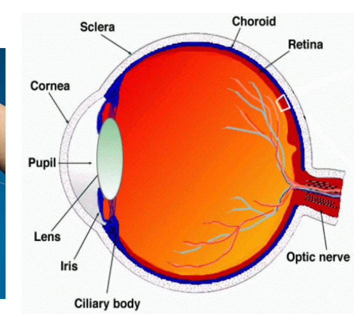
Reduced Materials Footprint: The role of nano

Research efforts should be aimed at reducing materials, energy, carbon footprints products via developing high performing materials.









Materials Sustainability: The role of Nano

Band edge type charge diffusion

Simultaneous energy & power density

Nano & Microcubes

Nanowires

Solar Cells

Multi tubular fibers

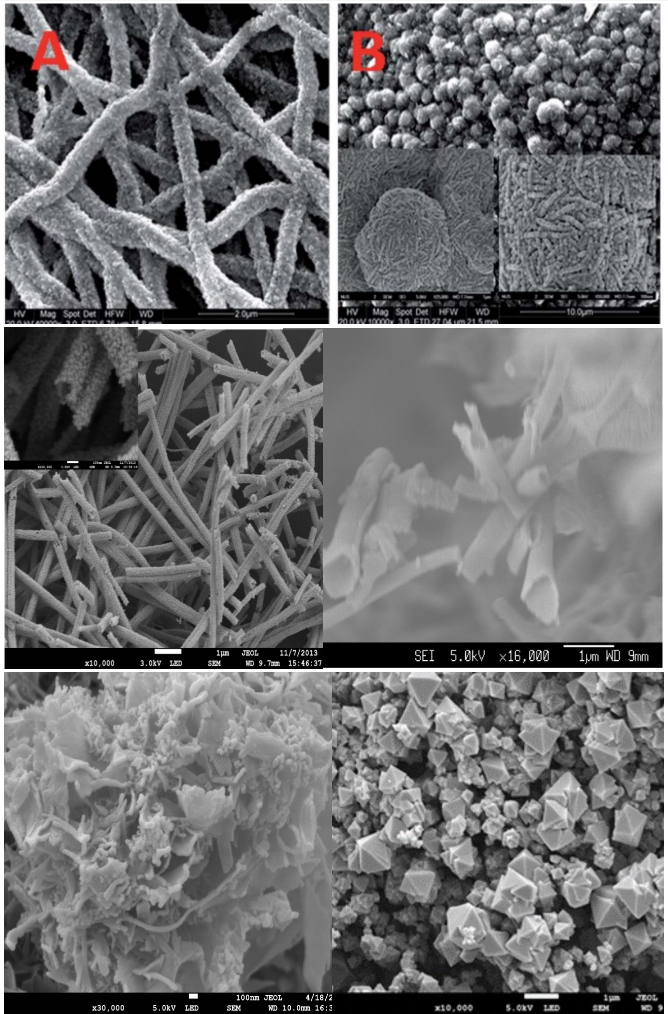
Nanoflowers

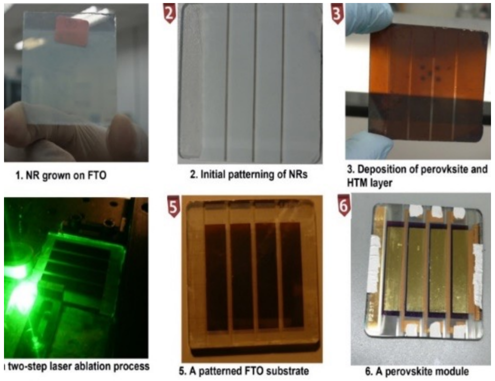
Batteries

Nanocomposites

Nanofibers

Supercapacitors





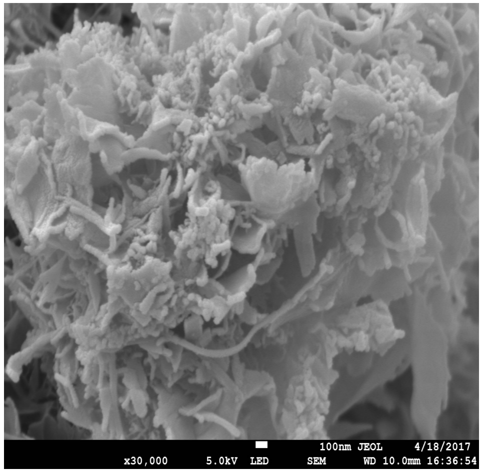
World's first nanorod solar module with efficiency ~15%
Gold medal for engineering excellence INPEX 2016, USA

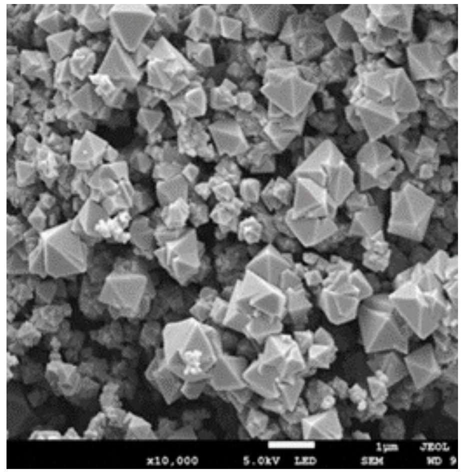
Hybrid supercapacitor; Gold medal; Invention of the Year, British Invention Show 2015

High carbon load, high embodied energy & high cost

Materials Sustainability: The role of Nano

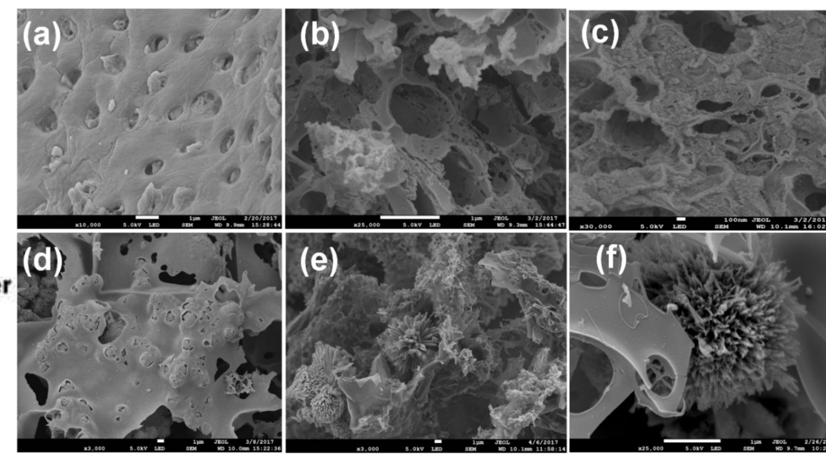
Improved materials efficiency: Less is more



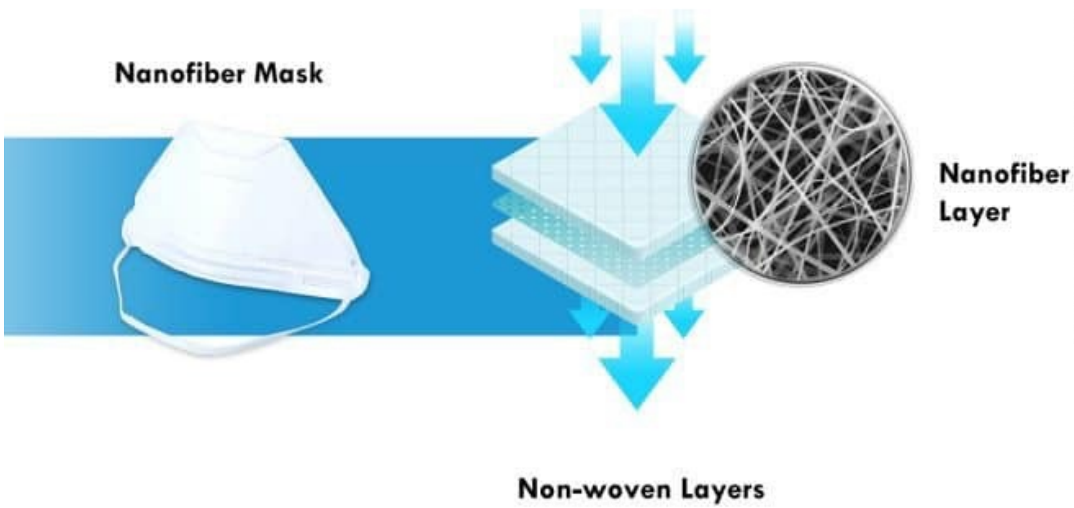


Fully Nano!

Not acceptable to industry.



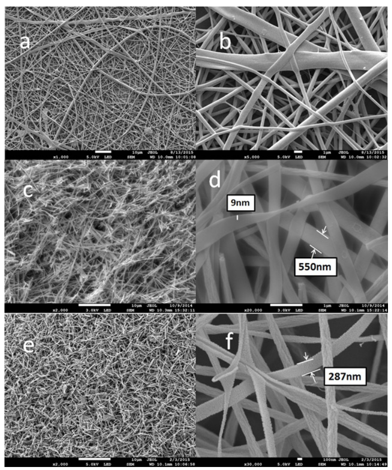
Less Nano!

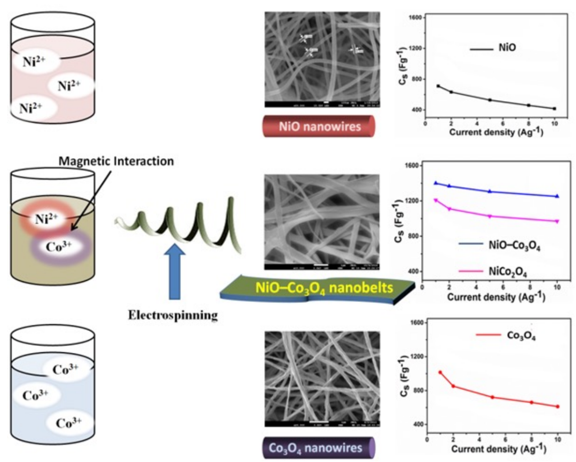


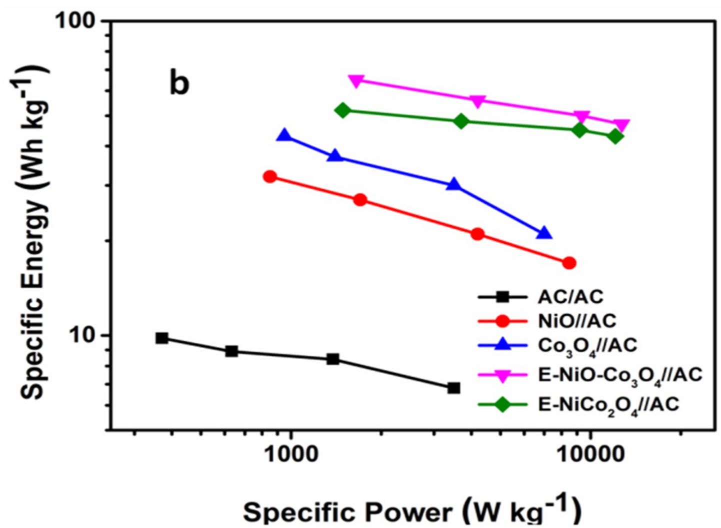
Noritake
JAPAN 1904

Materials with multifunctionalities

- Most device functionalities are not contained in a single material; therefore, Products are often made of multi-materials.
- Packaging containing multiple polymers and colors is an example of multi-materials in a product.
- Multi-materials system poses tough challenges during end-of-use solid waste management. Therefore, research and development efforts are to conceive and develop simpler materials with multi-functionalities so that they facilitate ease of identification, sorting, segregation, reuse, remanufacture, and recycle.







Multifunctional sustainable materials?

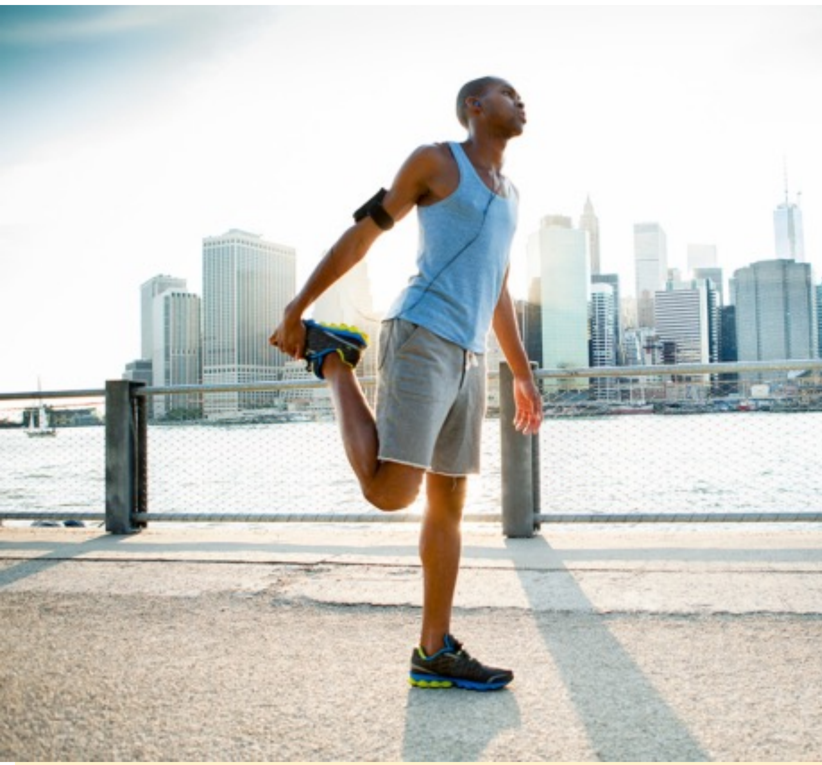
ACS Appl. Mater. Interfaces, 2017, 9 (12), pp 10730–10742
Materials & Design 122, 376 (2017)
Chem Eng J, 327, 962-972 (2017)
Journal of Alloys and Compounds 740, 703-710 (2018)
Electrochimica Acta 263, 524-532 (2018)

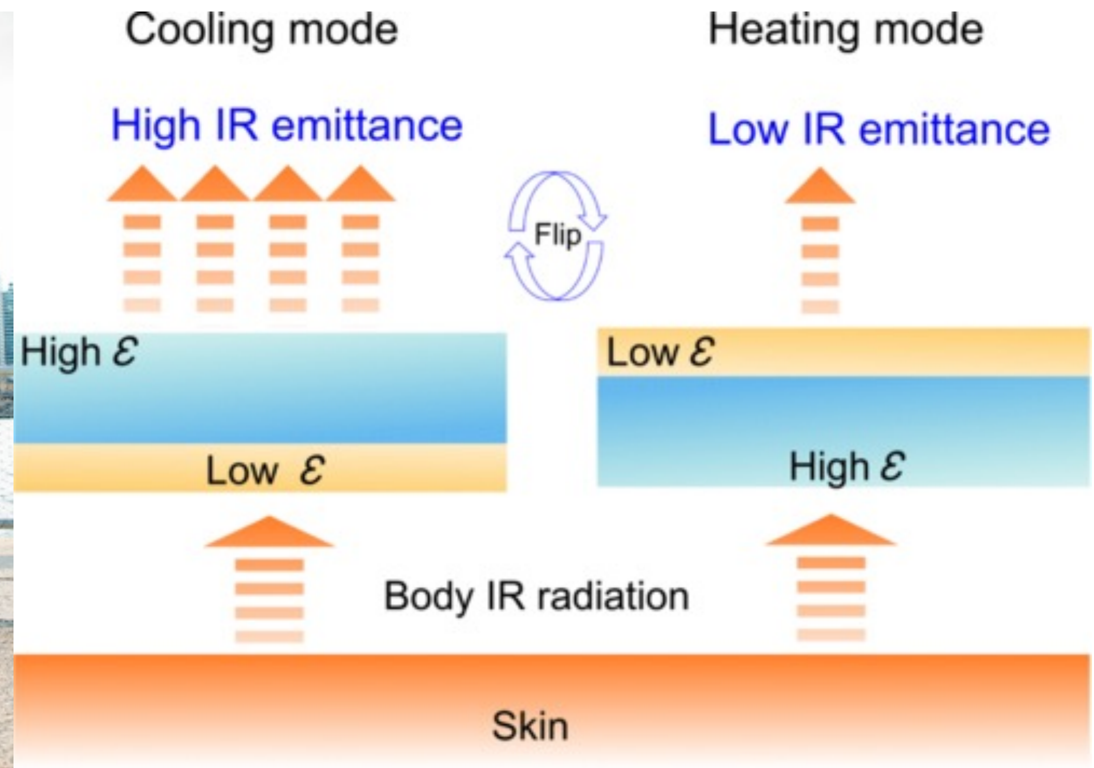
Multifunctional Materials

Janus materials are surfaces have two or more distinct physical properties.

Strong emissivity contrast is by utilizing both metallic and dielectric fibers within the yarn making the fabric.

'Janus textile' could keep you warm and cool you down





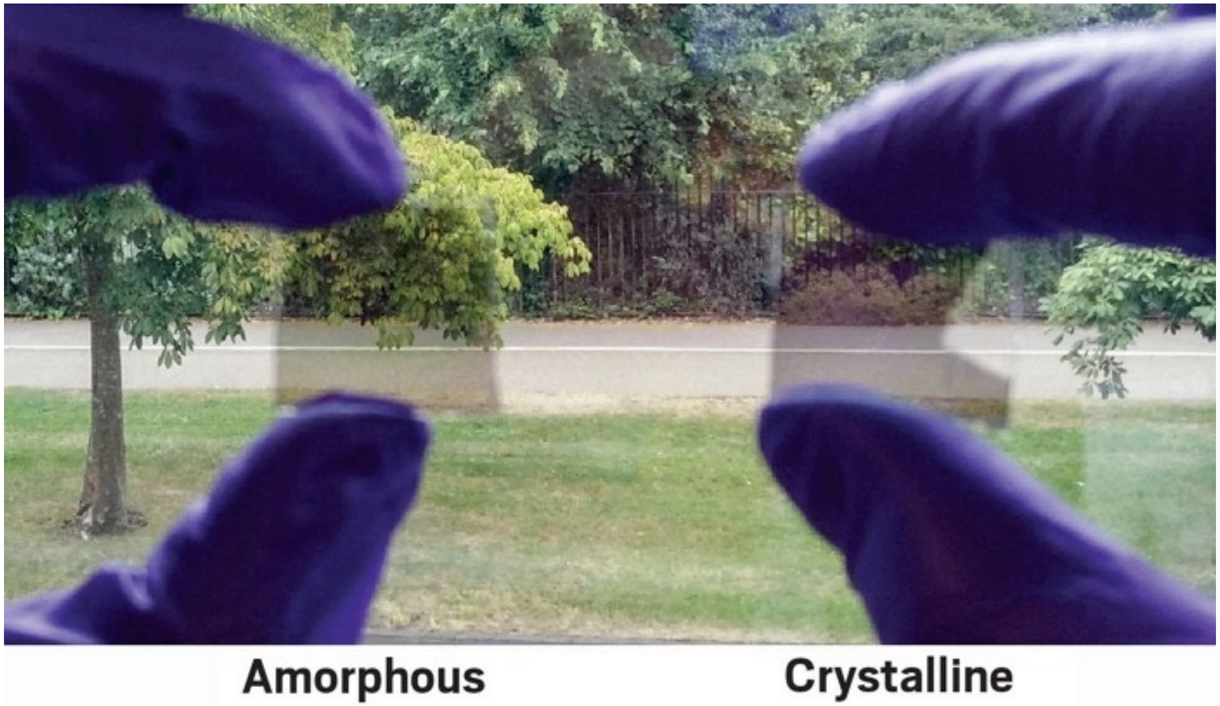
In this Janus textile, when a high-emissivity layer faces the ambient, the fabric is in cooling mode. Once the textile is flipped and the low-emissivity layer faces outside, the fabric is in heating mode. Theoretical design from University of Mons, Belgium.

Phys. Rev. Applied **16**, 054013 5 Nov. 2021

Multifunctional Materials

Switchable smart window coating can heat or cool a room

Phase-change material can convert sunlight into heat or reflect it while staying transparent



The heart of the coating is a 12 nm layer of a phase-change material, $Ge_{20}Te_{80}$, which can switch reversibly from a crystalline to an amorphous state when heated to 280–450 °C. As a proof-of-concept, the researchers deposited the coating on 25.8 cm^2 samples of glass. For commercial, double-pane windows, they propose putting it on the outside-facing side of the interior pane of glass.

ACS Photonics 2021, DOI: 10.1021/acsphotonics.1c01128

Materials of higher circularity

- Materials circularity is defined as the possibility to be economically repaired, remanufactured, recycled, upcycled or re-imagined.

- So far, performance, cost, properties, and processing are the focus of materials community to design and develop materials.

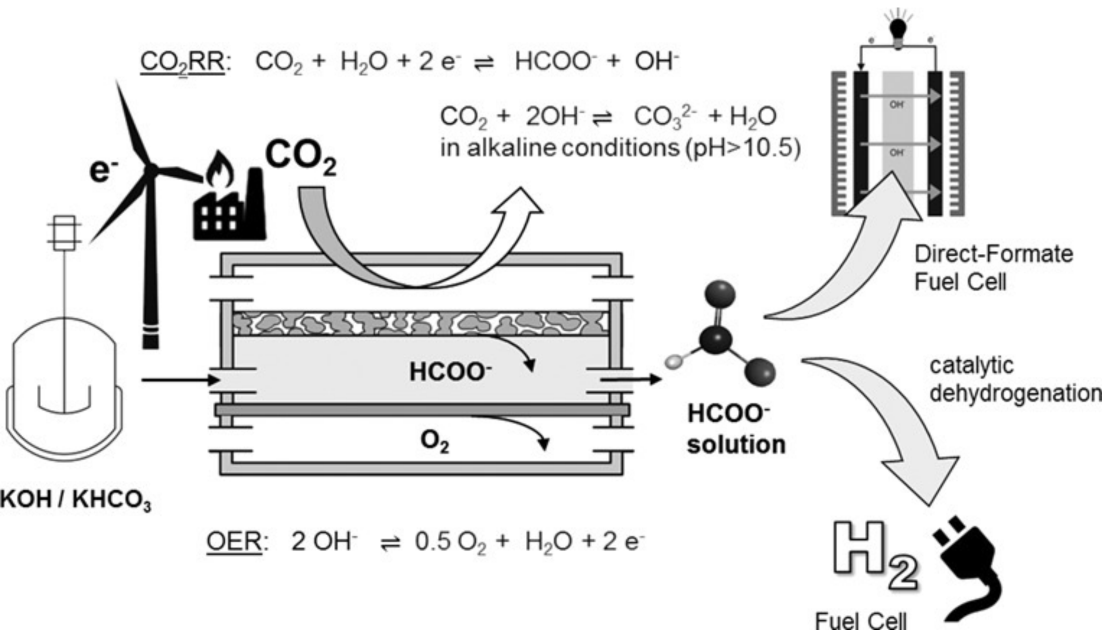
- Materials circularity must be an essential materials selection, design and development criterion for successful circular economy.

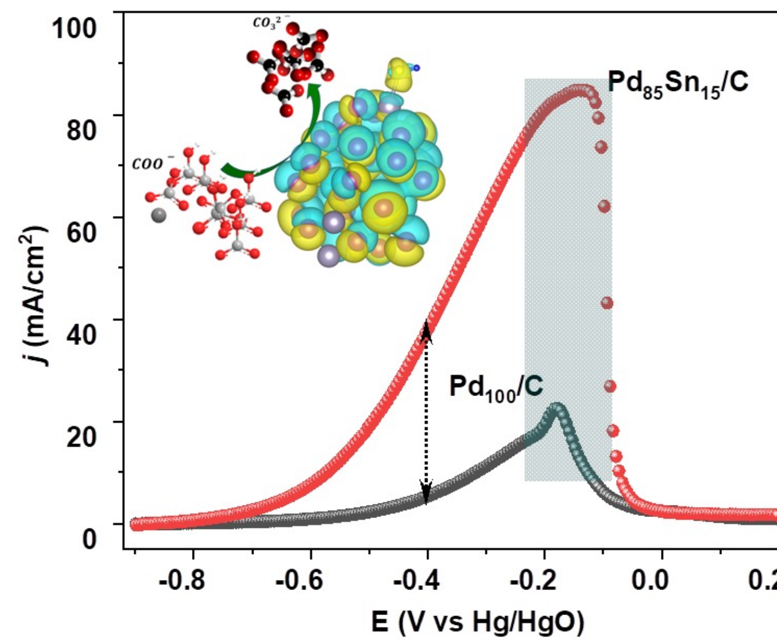
- For example, only ~20% of over 50 million metric tons of electronic waste generated annually is recycled.

- Significant attention is required to develop economically viable and environmentally benign technologies to increase materials circularity.

- A holy grail is to design and develop materials with perpetual circularity.

Circular Fuels





ACS Applied Energy Materials 5 (1), 266–277 (2021)

Lower over potential, higher current density and higher durability

Materials with enhanced durability

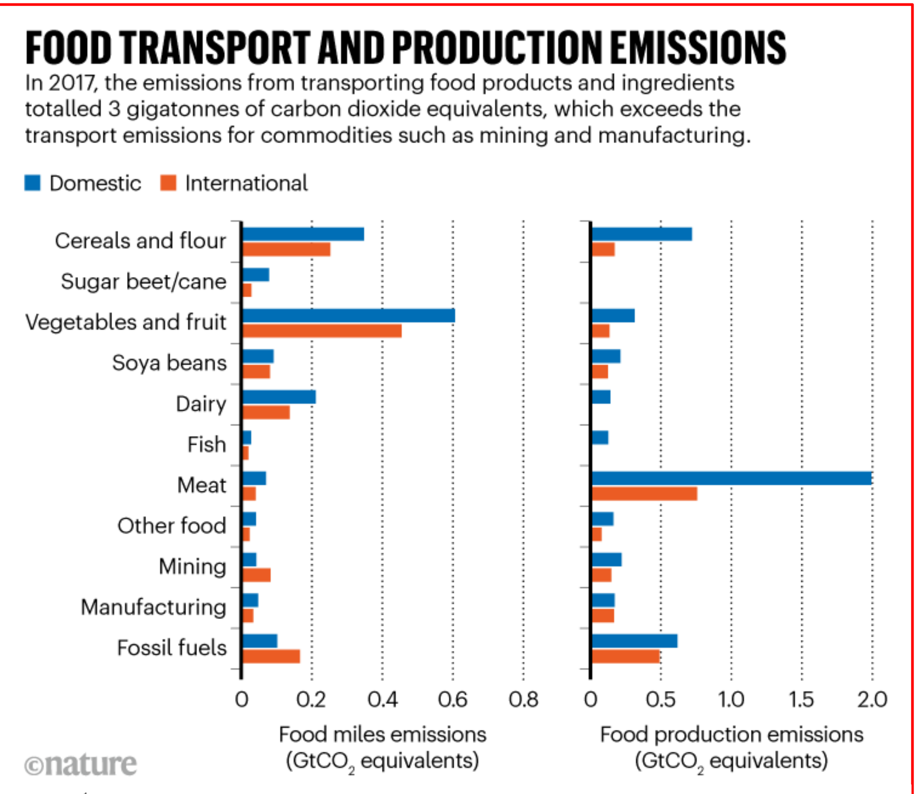
- Recent decades saw intentional design and selection of materials with shorter lifespans for business profits.

- For example, ~350 million metric tons of plastic is produced annually for short term use.

- This is causing growing volumes of solid waste worldwide and associated environmental and human health problems.

- Therefore, all materials as well as products should be designed and made for longer life spans and facilitate ease of repair and reuse, thus reducing the total solid waste sent into the Earth ecosystems.

MATERIAL MILES



Moving fruit and vegetables generated twice the amount of CO_2 produced than by growing them.

nature

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NEWS | 01 July 2022

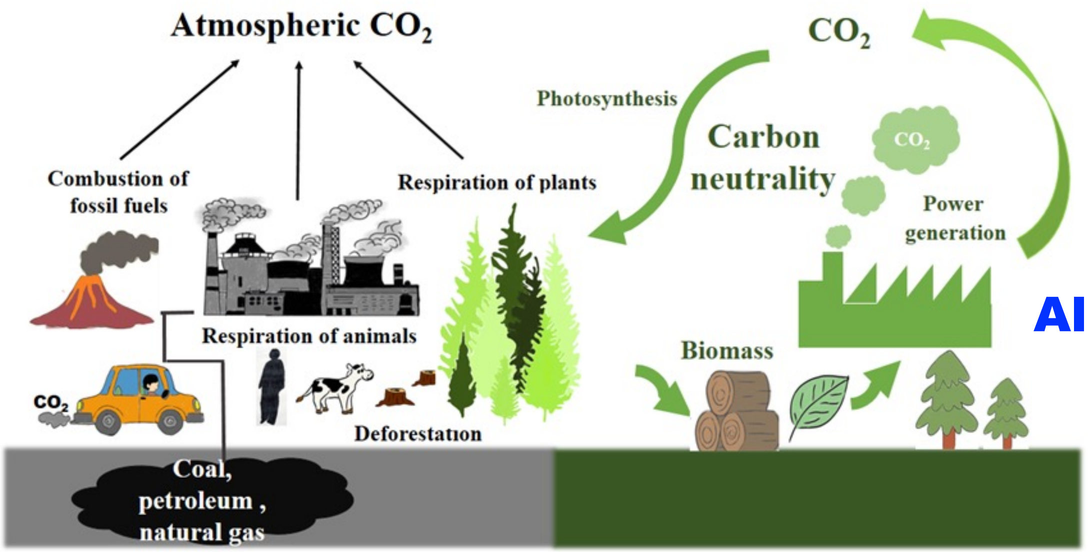
Transporting food generates whopping amounts of carbon dioxide

Moving fruit and vegetables in refrigerated vehicles is particularly emissions-intensive.

Why can't we produce it locally? Many modern agricultural protocols such as vertical farming, decentralized urban farming through keyhole garden (Mater Circ Econ. 2, 12, 2000)

Low carbon footprint, embodied energy, and renewability

Fundamental food production factory



All biomass is carbon negative!

- Hardest, most conductive, highly porous materials are realized from carbon.
- Nearly 200,000 Scopus indexed papers published in 2022 & 2023 on carbon.
- Cellulose nanocrystal is now getting developed as a multifunctional material.
- Bio-resoursable materials are of high environmental benignity, supporting natural habitat and human health, renewability, & lesser material miles.

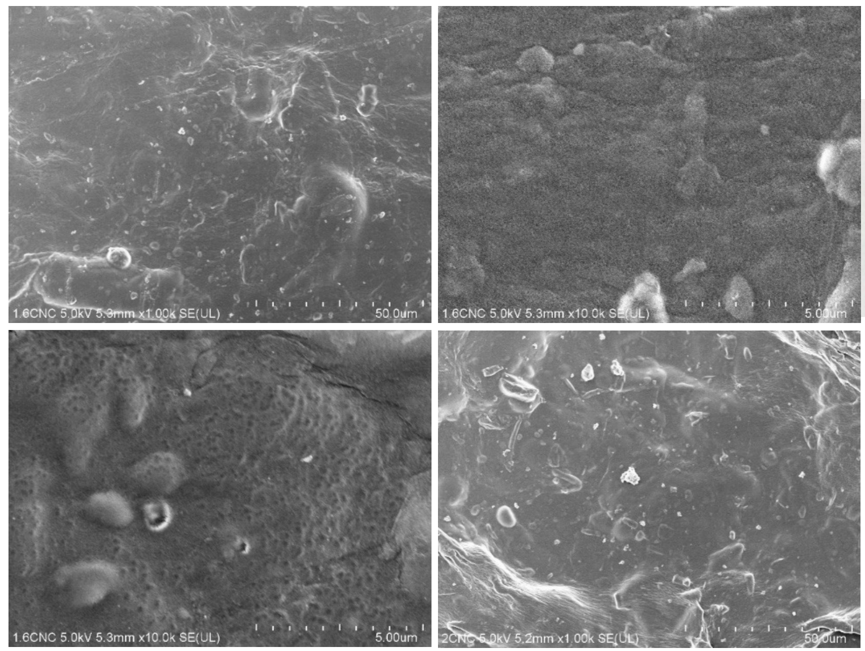
Low carbon – Low embodied energy materials

CNC toughened seaweed: A renewable, clean & all-plant based drug delivery medium

- **Hard capsule** – easy and versatile drug delivery carrier
- Present use of gelatine (animal based)
- 40 % **Porcine** skin, bones
- Cow – **Foot Mouth Disease**
- 1.6 billions Muslims
- 200 millions vegetarian
- Present vegetarian- **expensive**

inexpensive, easy cultivation & renewable

Nanocrystals as a property modifier/enhancer



Comparable disintegration time & strength as that of gelatine-based capsules

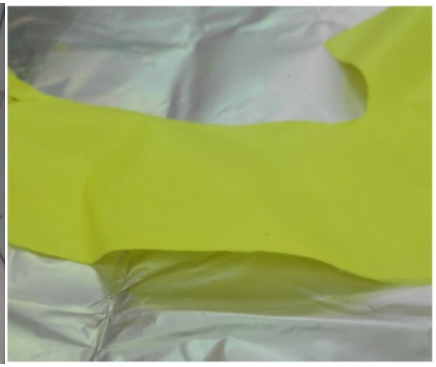
Adam et al; Chemical Engineering Communications 208 (5), 741-752 (2021)

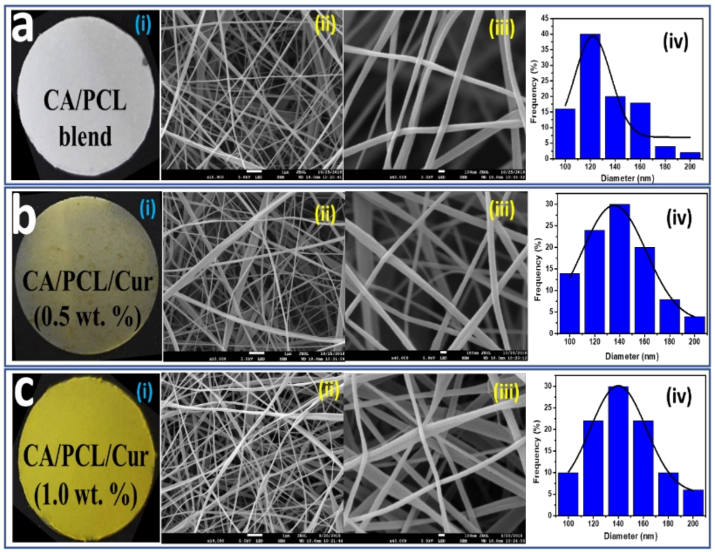
Biowaste resourced cellulose as fibre cloths for membrane application

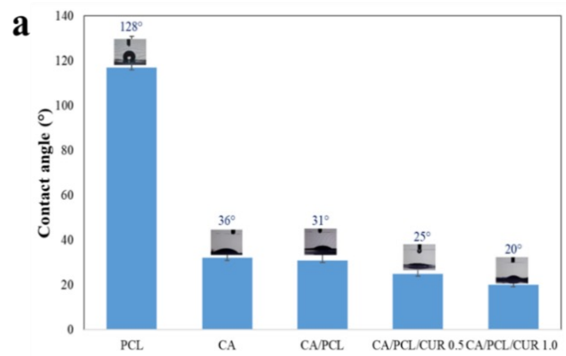
1. PI 2018000713 (Dated Feb 2018);
2. PI 2019000229 (Dated March 2019)

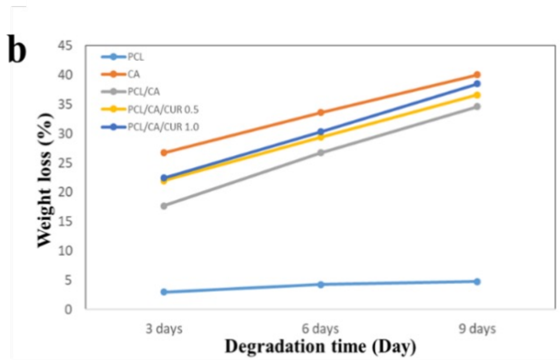
Portfilt

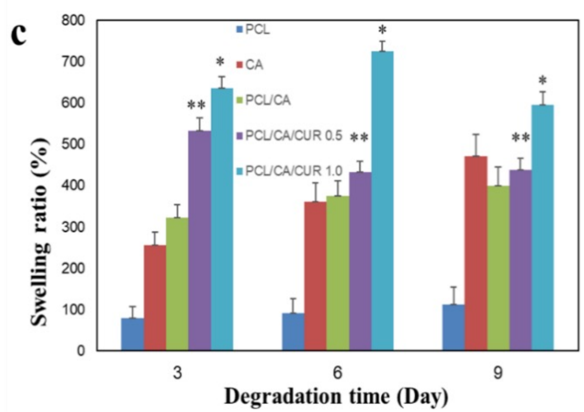
CURCUMIN-LOADED CELLULOSE FIBERS CLOTHS FOR TISSUE ENGINEERING

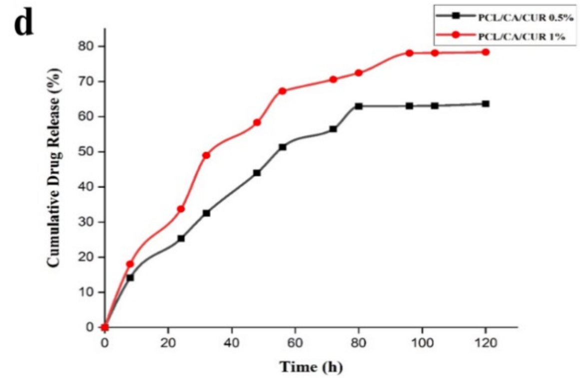


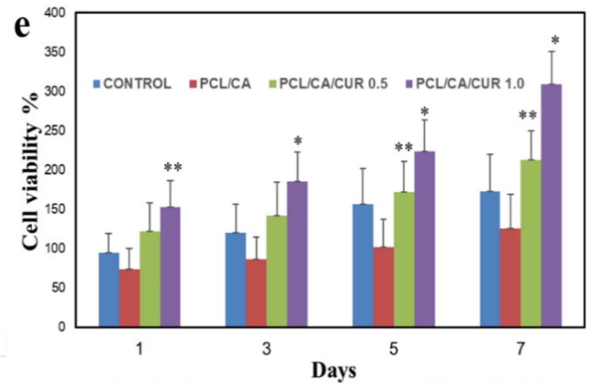


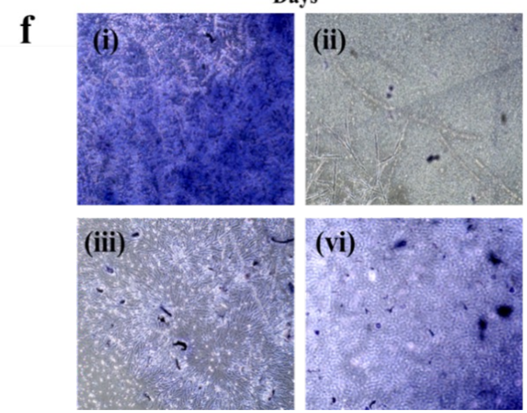








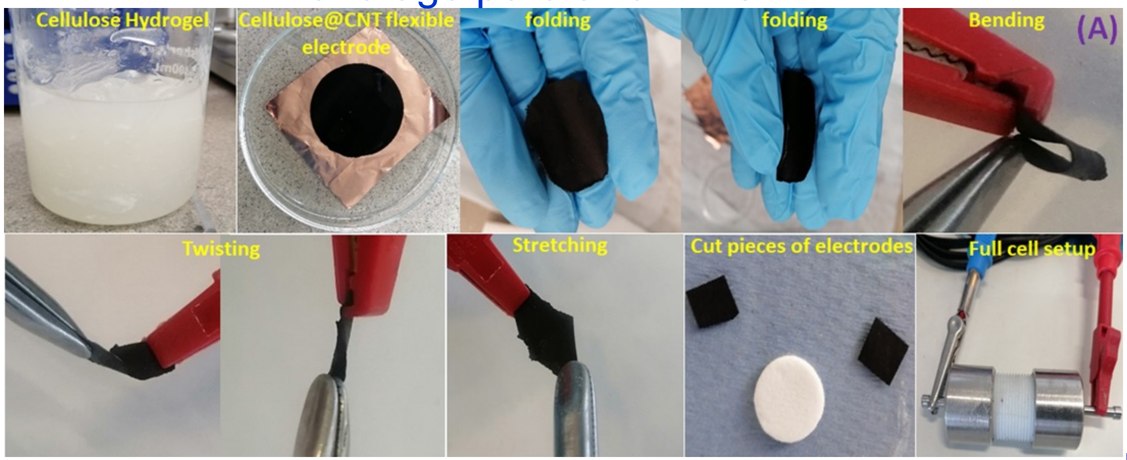




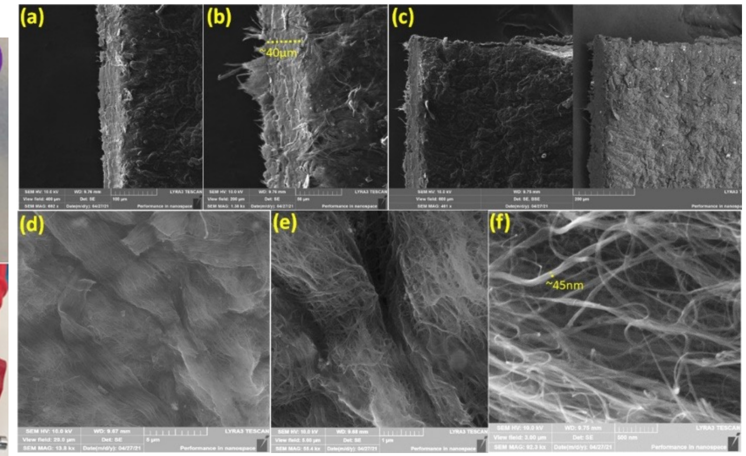
Nurul Nadirah, Amina et al. Int. J. Biol. Macromolecules 198, 147-156 (2022)

Cellulose-CNT electrodes//cellulose-hydrogel electrolytes

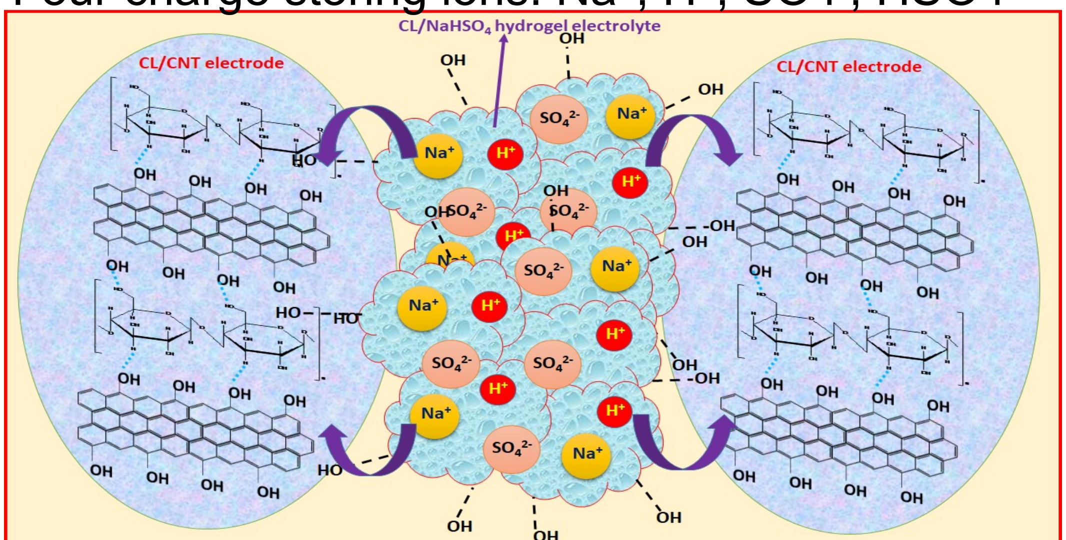
The BET ~478 m^2/g, Pore volume 1.46 ml/g, average pore size ~ 4.87 nm.



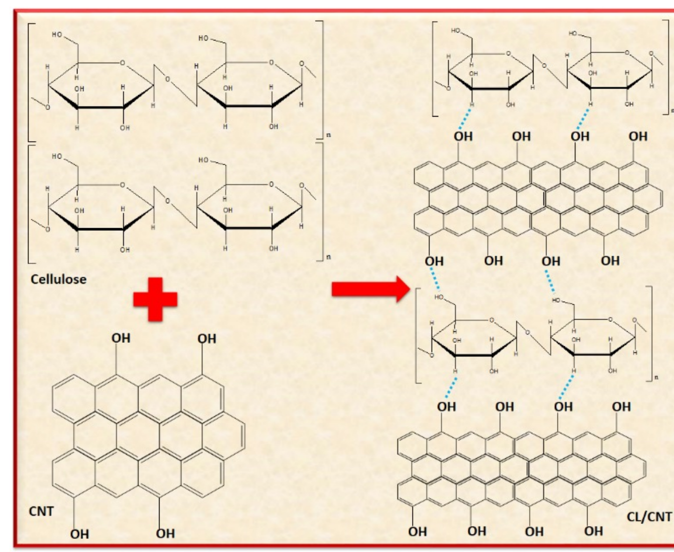
40 microns thick films



Four charge storing ions: Na^+, H^+, $SO4^-$, $HSO4^-$



Hydrogen bonding & van der Wall interaction improved flexibility



E_S ~135 $Wh{\cdot}kg^{-1}$; P_S ~1.9 $kW{\cdot}kg^{-1}$

B. Pal et al, Electrochemica Acta, Volume 415, 20 May 2022, 140239

Porous carbon from bioresources

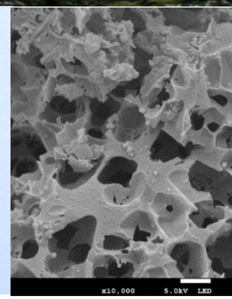
100 kg biomass / 2.5 kg crude palm oil

5 – 6% PKS

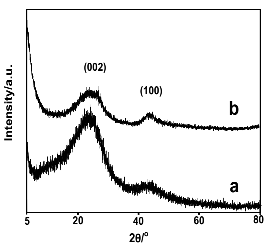
Carbon, Kernel Oil

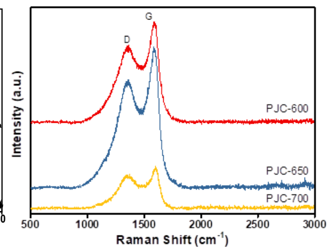
20 – 25% EFB

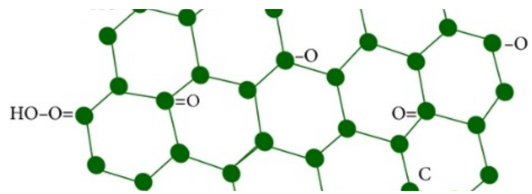
Starch, Cellulose



dry weight basis (%)	Jamaluddin et al. (2011)	Idris et al. (2010)	Adinata et al. (2007)
Volatile matter	77.5	69.2	72.47
Fixed carbon	20.3	16.0	18.7
Ash	2.2	10.5	1.1







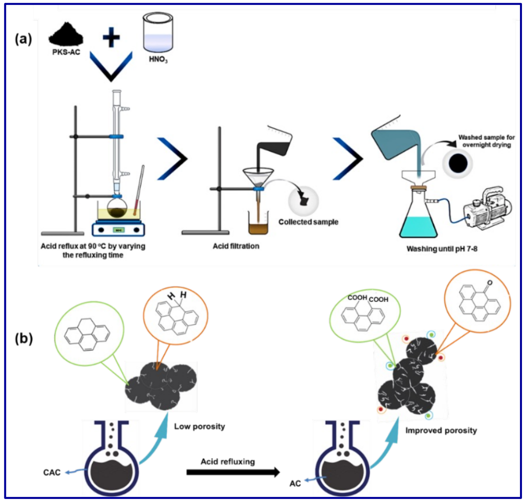
Element	(%)
C	47.66
H	6.17
N	0.80
S	2.47
O	41.13
Ca	1.94

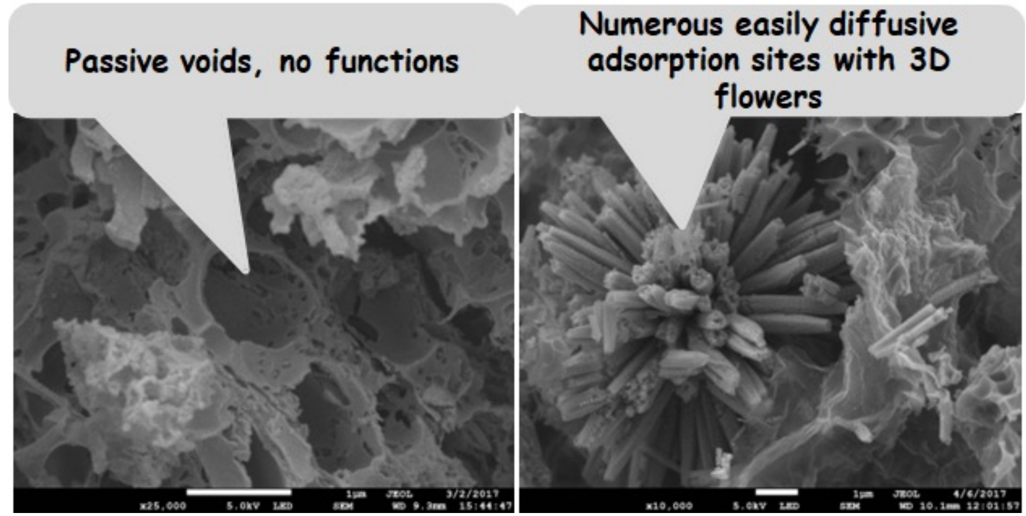
Carbon	d_{002} (nm)	d_{100} (nm)	L_c (nm)	L_a (nm)	L_c/L_a	N_p (L_c/d_{002})
AC-C	0.376	0.205	1.368	3.093	0.442	3.634
AC-P	0.372	0.210	1.116	3.740	0.299	3.000

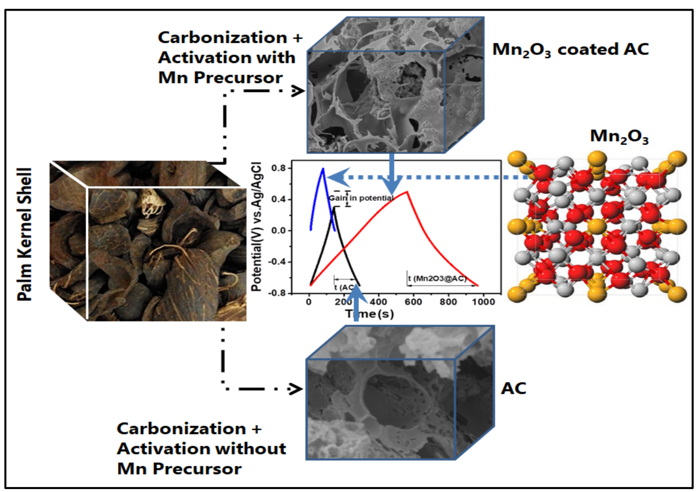
Activated Carbon	AC-C	AC-P
S_{BET} ($m^2 g^{-1}$)	460 – 470	720 - 730
Pore size (nm)	1.4 nm, 9.3 nm	1.5 nm
C_s (single electrode) @1 A/g	210 (KOH)	123 (KOH)

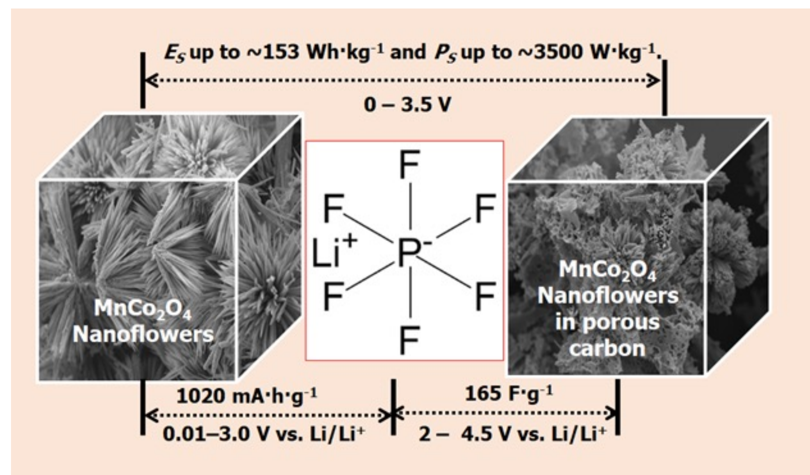
Misnon et al; Electrochimica Acta 174, 78-86 (2015)

Adopted Strategies





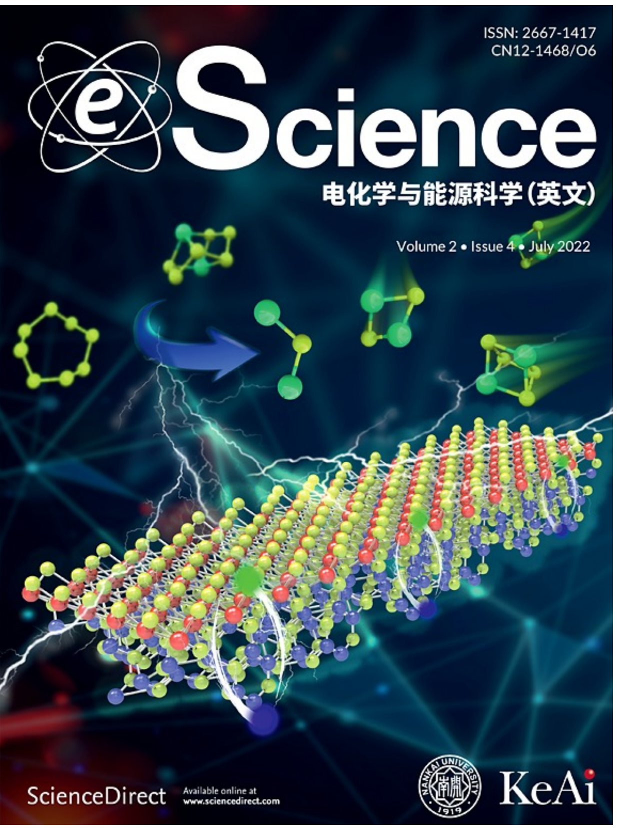


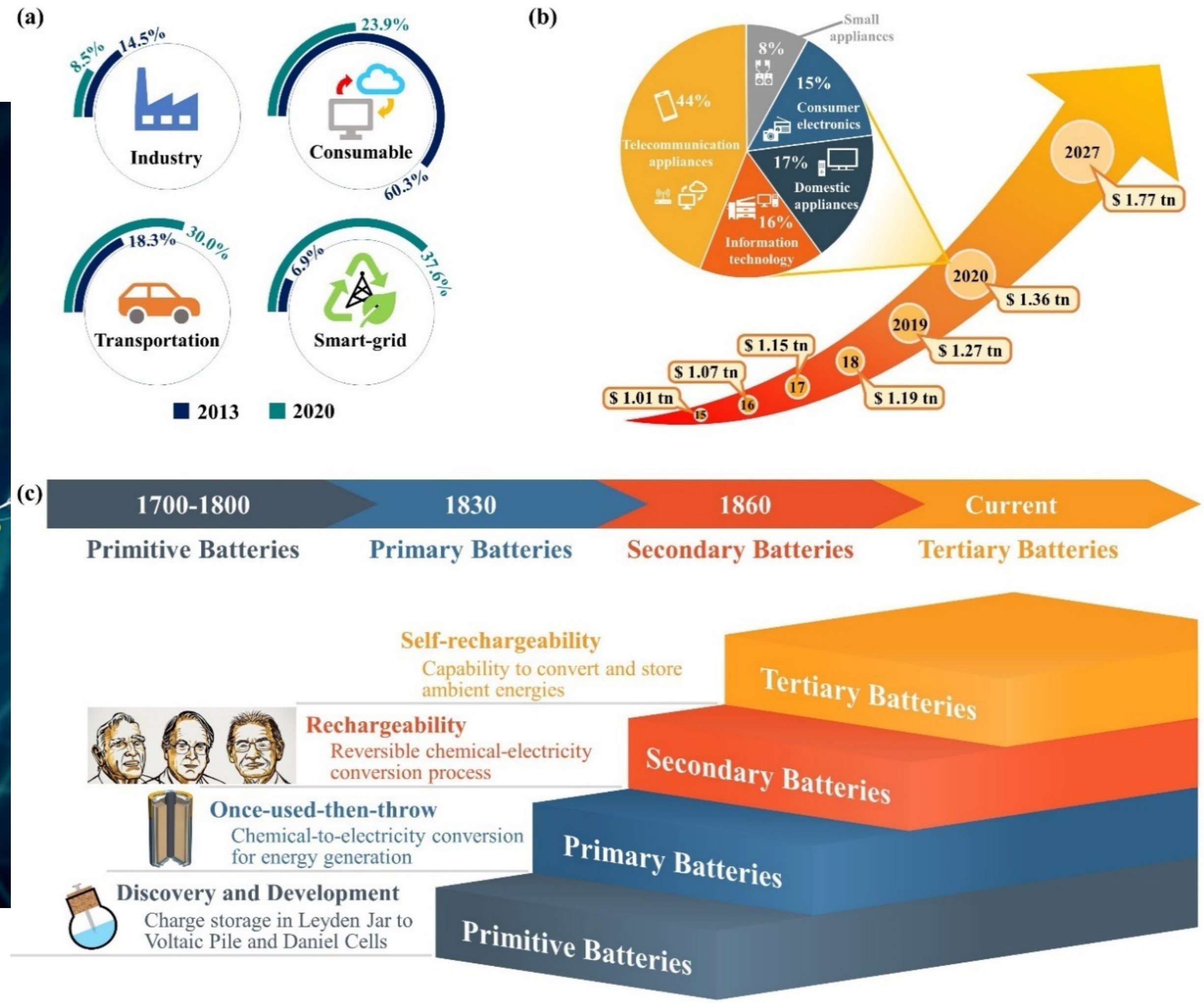


J. Power Sources 489, 229522 (2021); J Colloids & Interface Sci 562, 567-577 (2020); Energy & Fuels 34 (4), 5072-5083 (2020); Journal of Alloys and Compounds 858, 157649(2021); Energy & Fuels 35 (16), 13438-1 3448 (2021); Electrochimica Acta 174, 78-86 (2015)

Self-rechargeable batteries for sustainability

Next major development in energy storage is most likely to revolve around providing energy to power wearable/micro-electronics without engaging energy grid.

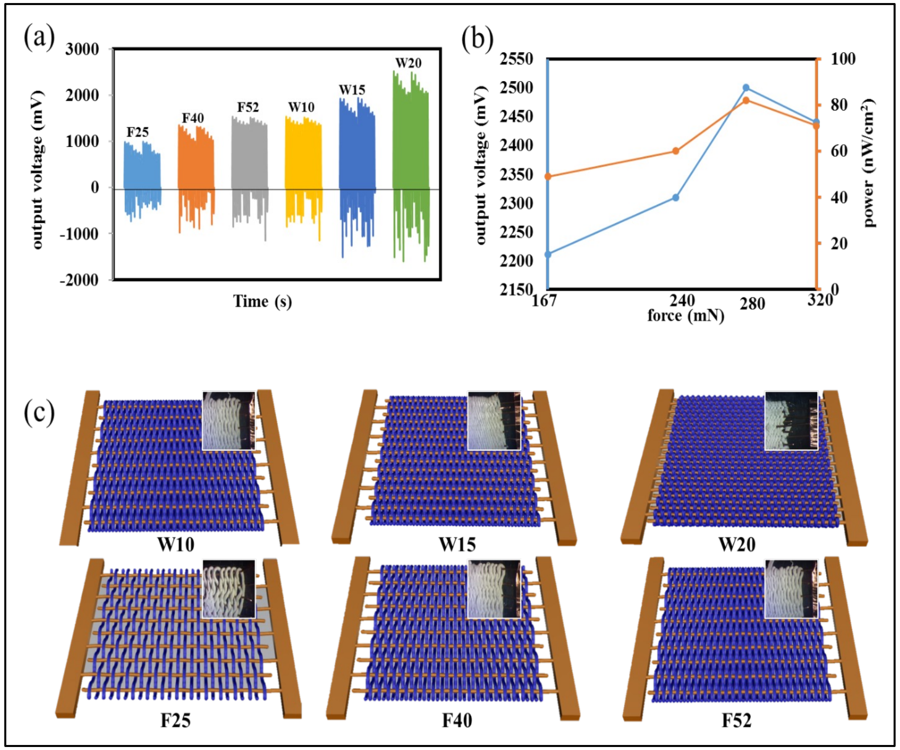


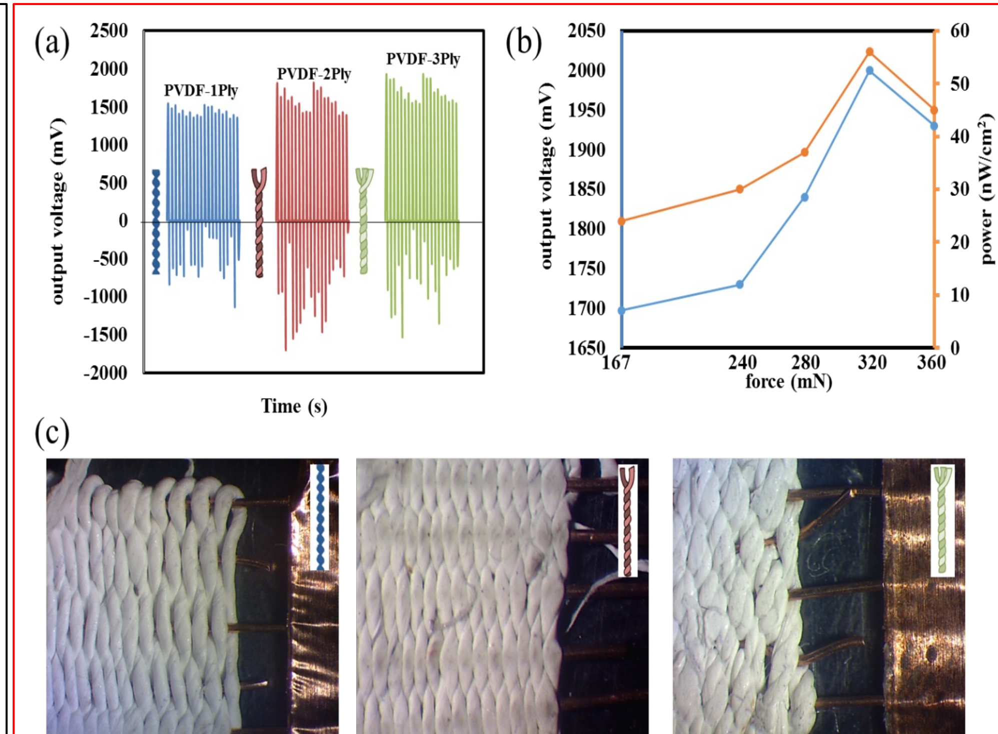


JK Ling et al; eScience 2 (4), 347-364 (2022)

High voltage yarns from aligned fibers

P(VDF-TrFE)





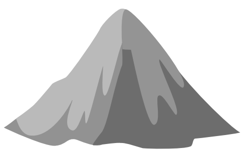
- **Voltage >2.2 V; power ~nW → low values of piezo electric current**
- **Materials engineering to enhance the current through it.**

Amin et al; Macromolecular Materials and Engineering 306 (1), 2000510 (2021)

Current Circularity Progress in PSCs

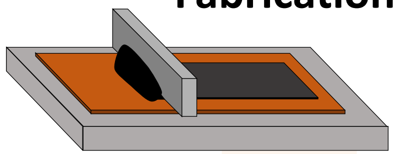
JK Ling et al; Solar RRL 5 (11), 2100401 (2021)

Increasing focus on Sustainability



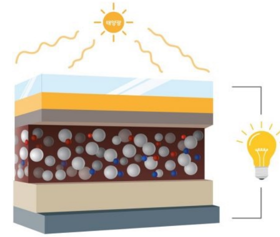
Sourcing Materials

- Sourcing lead from degraded devices
- Sourcing lead from lead-acid battery



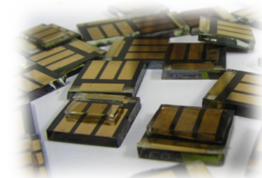
Device Fabrication

- Recovering of solvent
- Recovering precursors
- Reduce processing step



Operation

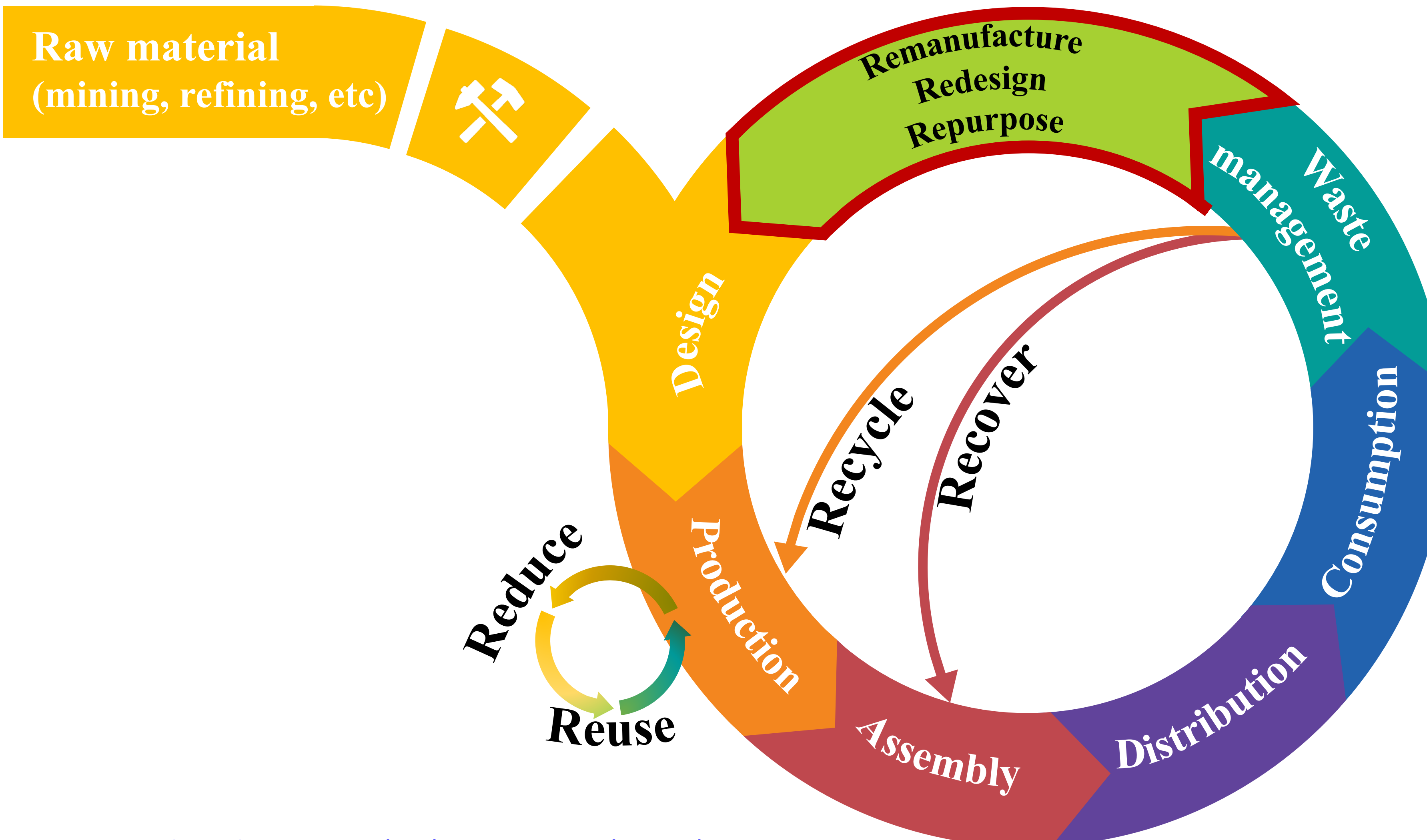
- Reducing lead leakage
- Applying sealant
- Developing lead-free perovskite
- Improving material properties



Disposal

- Recovering conductive glass
- Recovering precious metals (Counter electrode)
- Recovering perovskite precursors (mainly PbI_2 through DMF immersion)
- Performance recovery either via MAI treatment or high potential treatment

Challenges, Opportunities, Research Gaps in Sustainability of PSCs

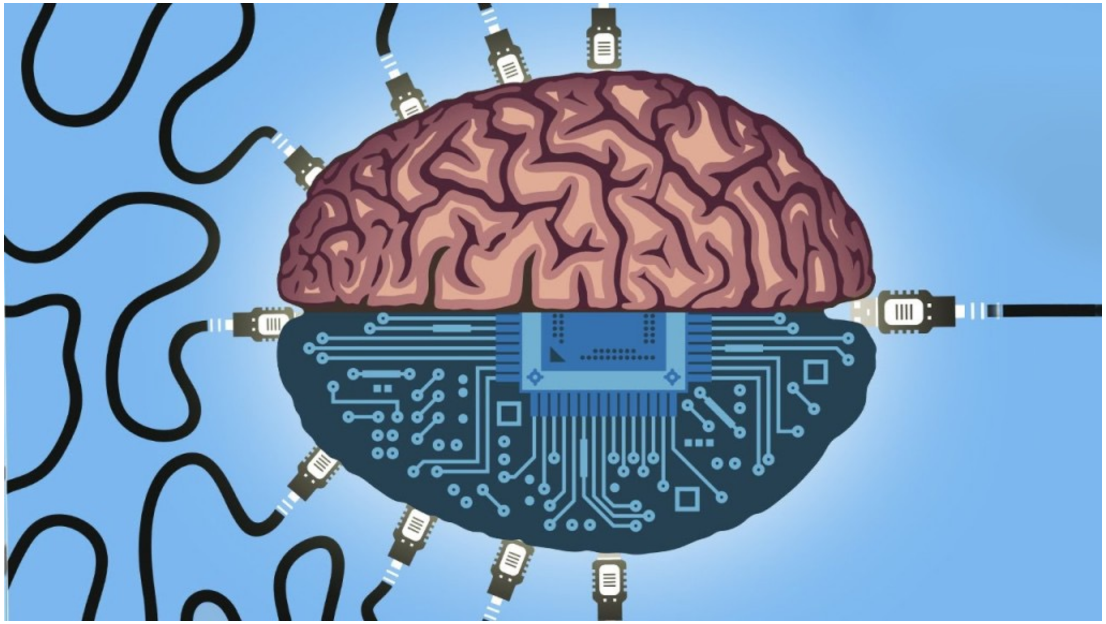


JK Ling et al; Solar RRL 5 (11), 2100401 (2021)

Existential Challenges: Speeding the delivery process

Augmenting huma abilities with data science, ML, ad AI

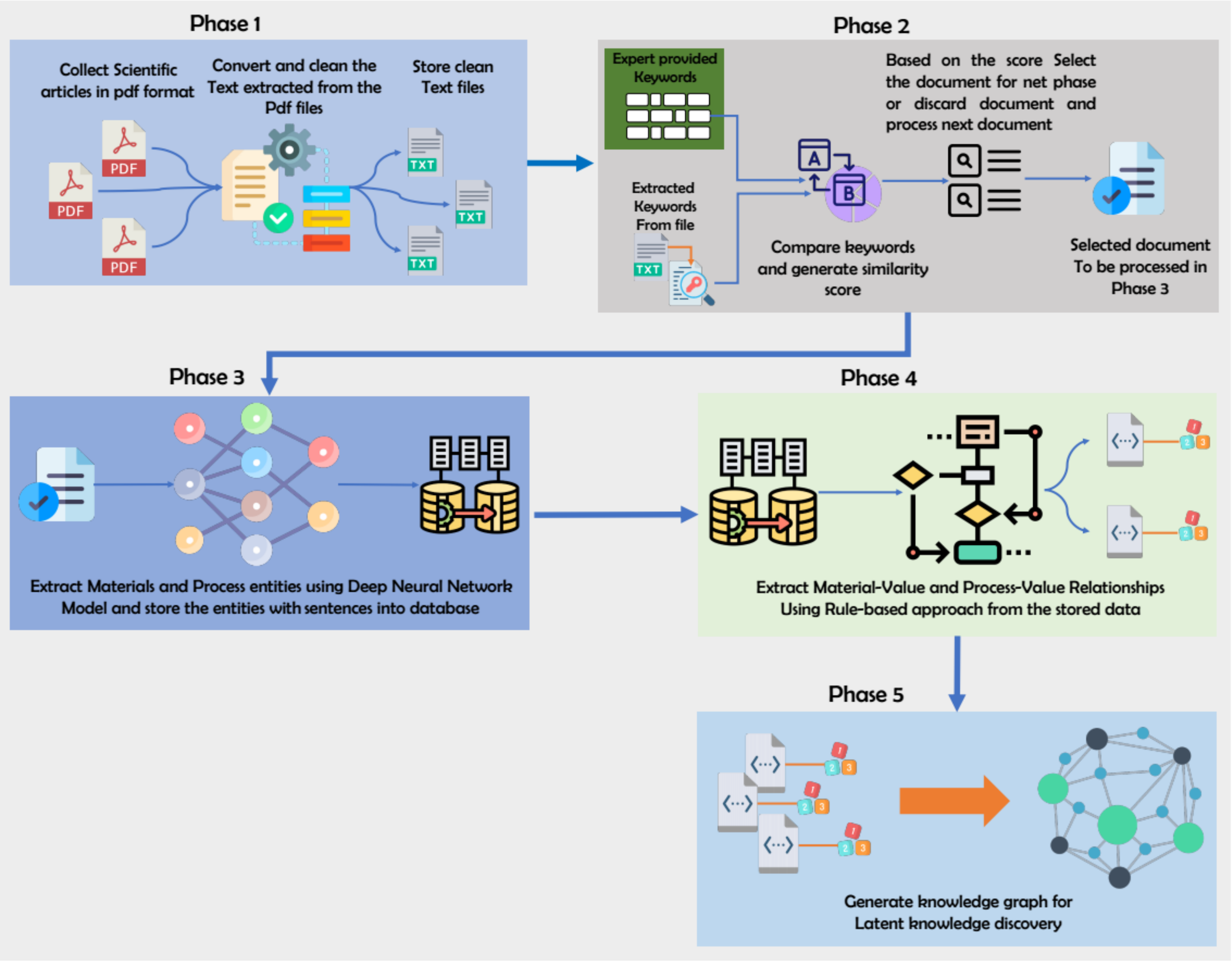
Human brain engage in trillions of calculation per second but via parallel processing; and most of this capacity is utilized to keep our lives.



Modern computers have only a fraction of this capacity but can be programmed for sequential calculations such that huge data can be handled at ease. If trained to answer our questions, we could solve the existential issues at unprecedented speed!

"ML will not replace scientists, but scientists who use ML will replace those who does not."

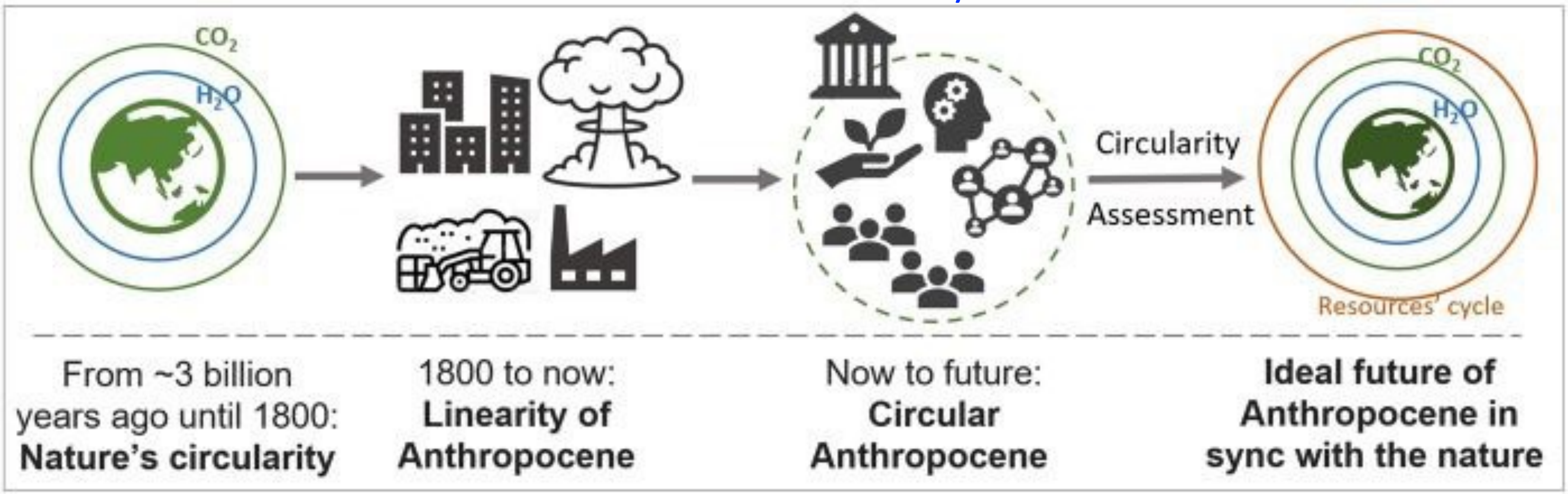
MatRec: An automated materials and processes identification tool using deep learning approach



Advanced Engineering Informatics (Revised, April 2023)

Conclusions: The four phase of circularity

Courtesy: Professor Seeram Ramakrishna



Phase 1: Nature's circularity by evolution
Phase 2: Creation of a linear economy through IRs
Phase 3: Our realization and attempting to charter towards circular economy
Phase 4: A sustainable planet through innovation, responsible behavior, and value contribution by the stakeholders (producers, businesses, consumers, and circularity professionals)

THANK YOU!