Key Innovations and Challenges in Soil Remediation for a Sustainable Future

Frederic Coulon and Tony Gutierrez

Cranfield University

EBNet

HERIOT WATT UNIVERSITY

Importance of the soil environment

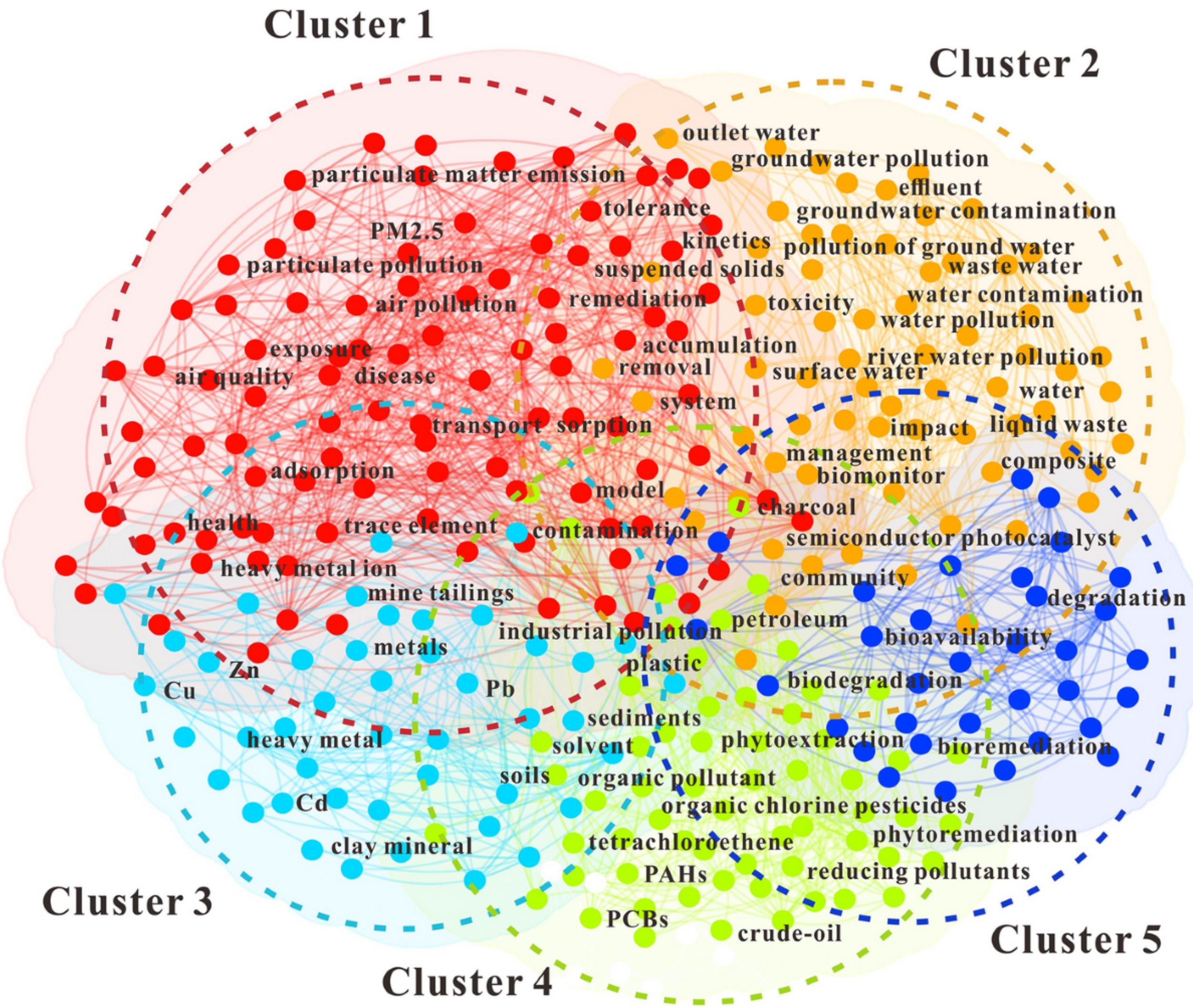
- Soils are an essential component of terrestrial ecosystems. Approx. 1 g soil contains 1x 10^6 bacteria.
- Plants and microbes interact with each other in biogeochemical cycles and can significantly alter nutrient availability.
- Of total area of world's land mass (13.07 x 10^9 ha), only 11.3% is cultivated for crops, 24.6% permanent grazing, 34.1% forest and woodland, 31% other land e.g. urban/ industry.

Why shall we prevent soil pollution?

- Soil is a **non-renewable natural resource**
- Important resource for food production, etc.
- Soils are increasingly degrading or irreversibly lost across the developed countries (US, EU, Japan....)

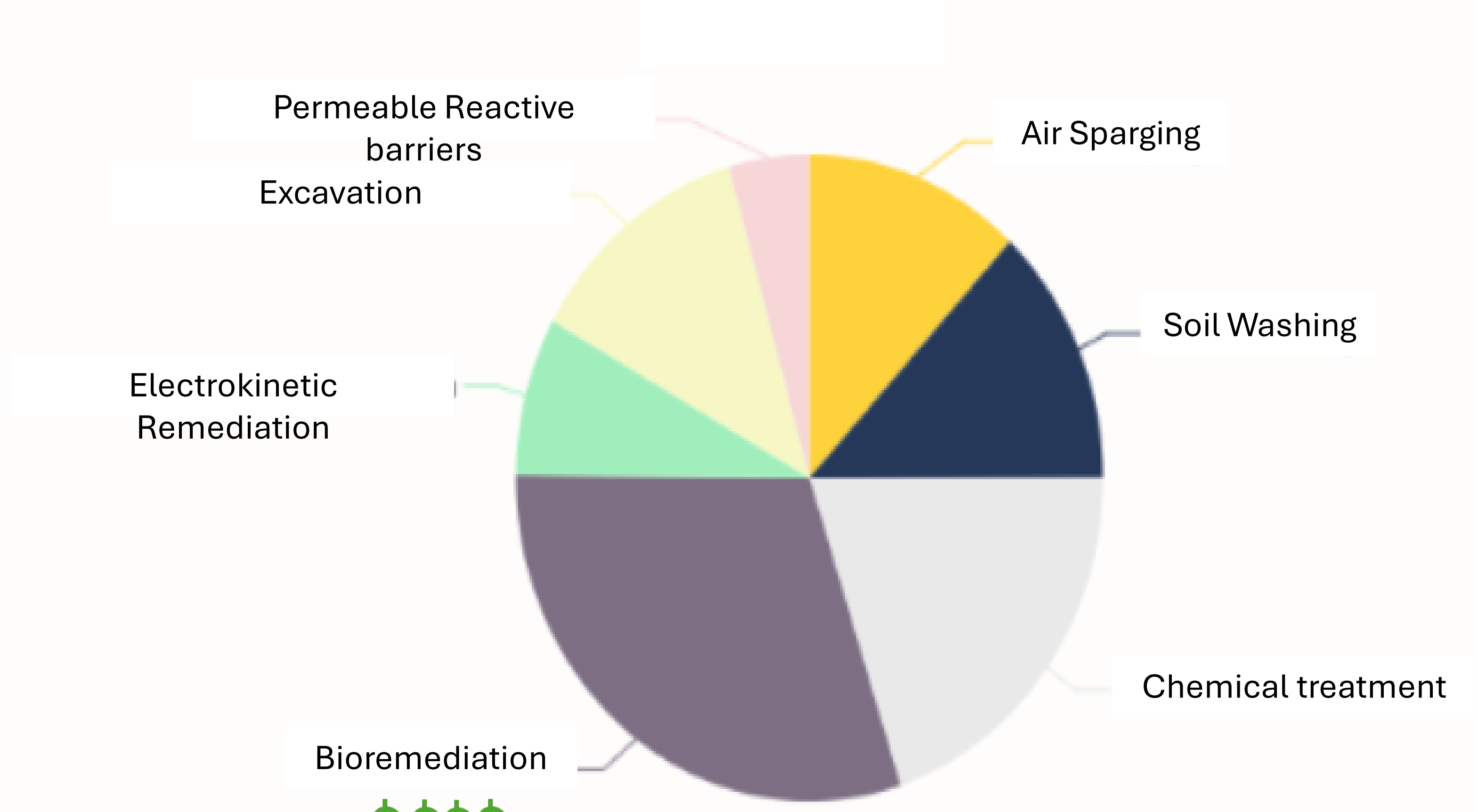
Soil remediation challenges

- A major challenge in soil remediation is the **diversity of contaminants** present in the soil.
- Contaminants can be of different types, such as heavy metals, pesticides, organic compounds, and emerging contaminants



Gao et al, 2024, Environ Dev Sustain, https://doi.org/10.1007/s10668-024-04676-5

Remediation technologies growth and innovation



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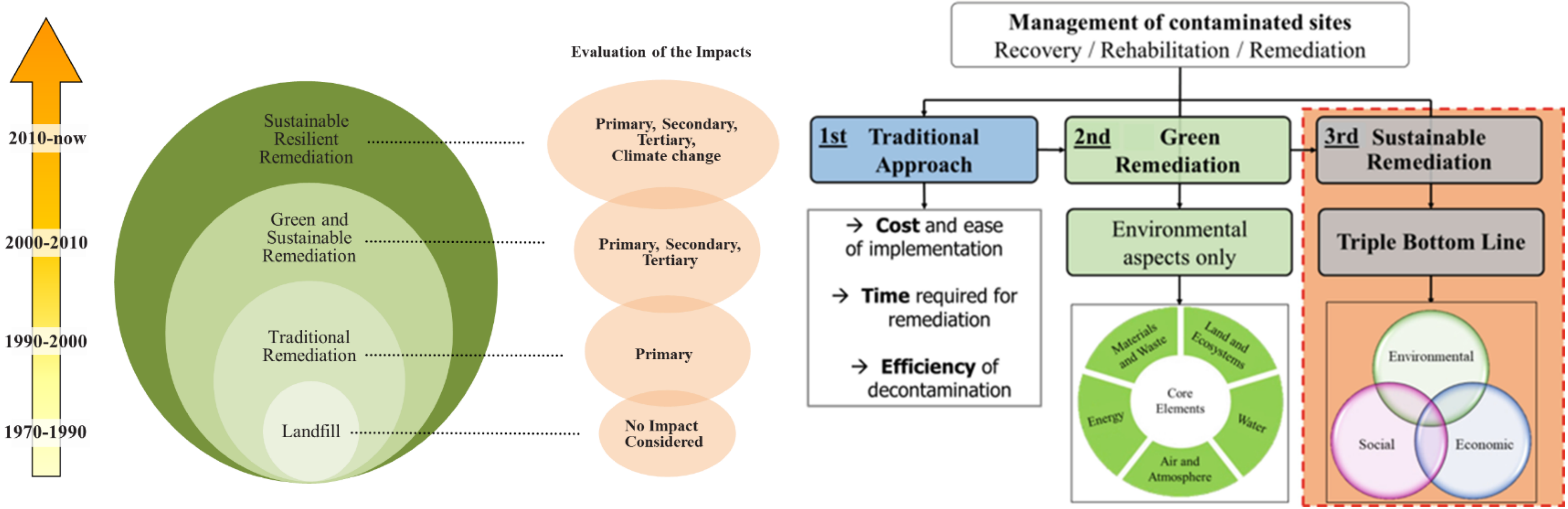
Most lucrative 2023 -2031

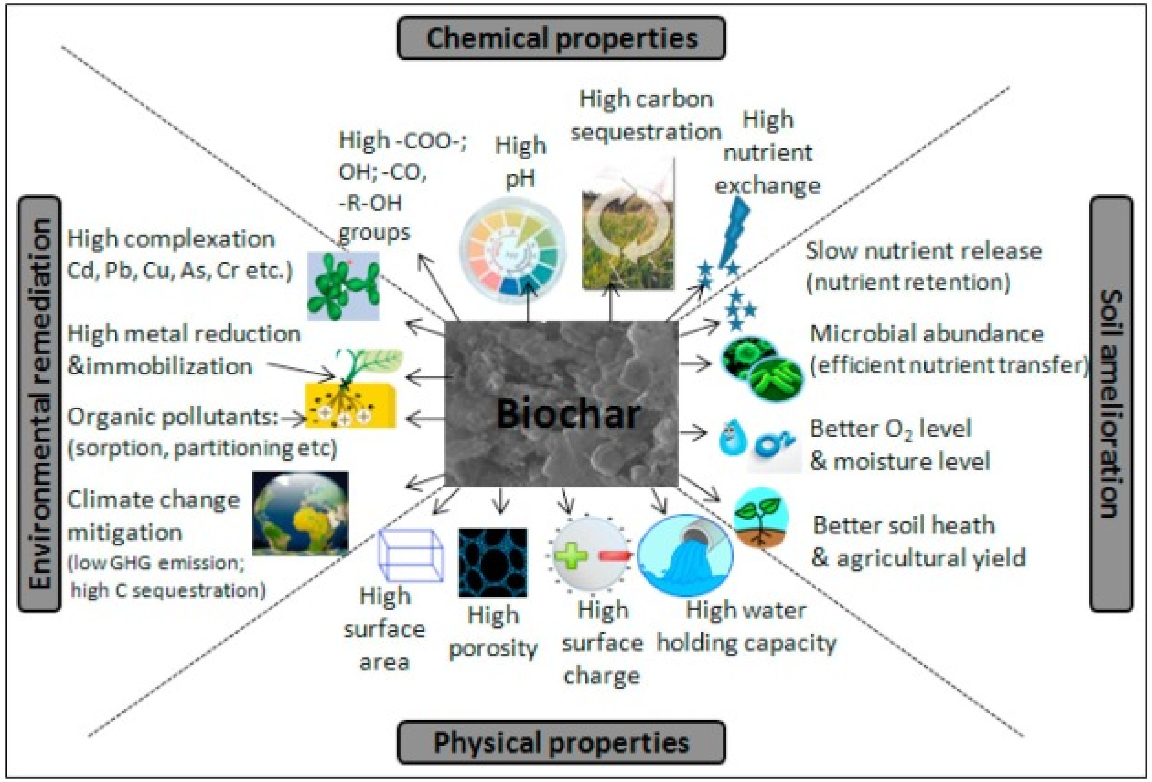
https://www.alliedmarketresearch.com/environmental-remediation-market-A15965

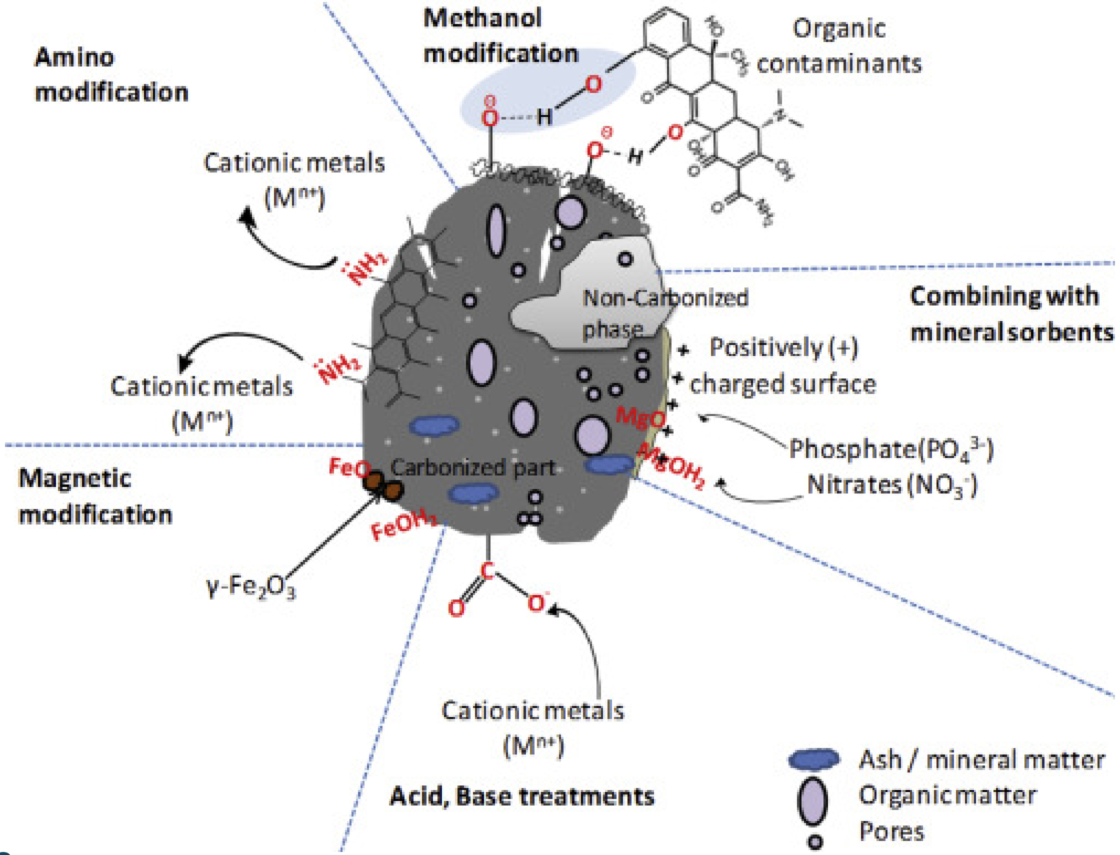
Evolution of remediation approaches



(Grifoni et al 2022, Environments 2022, 9, 18)

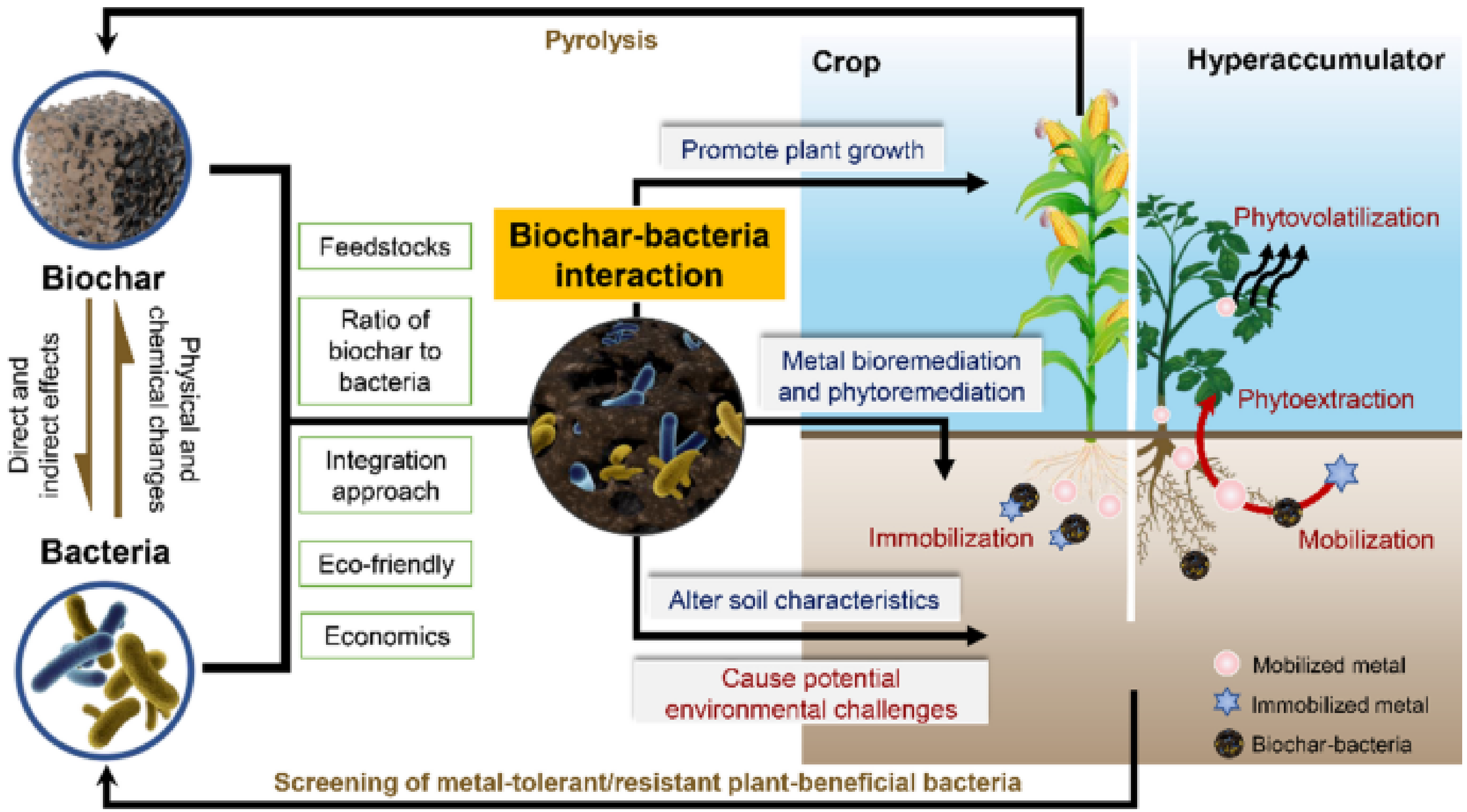
Relevance and application of biochar as tool for soil





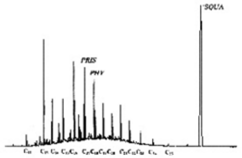
Das et al., 2021; https://www.intechopen.com/chapters/76192

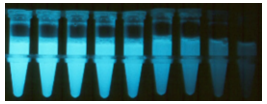
Integrating biochar and bacteria for sustainable soil remediation

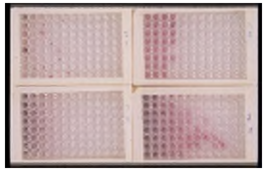


Ouyang et al. 2023. Biochar, 5:63

Predicting remediation: the "Algorithm"



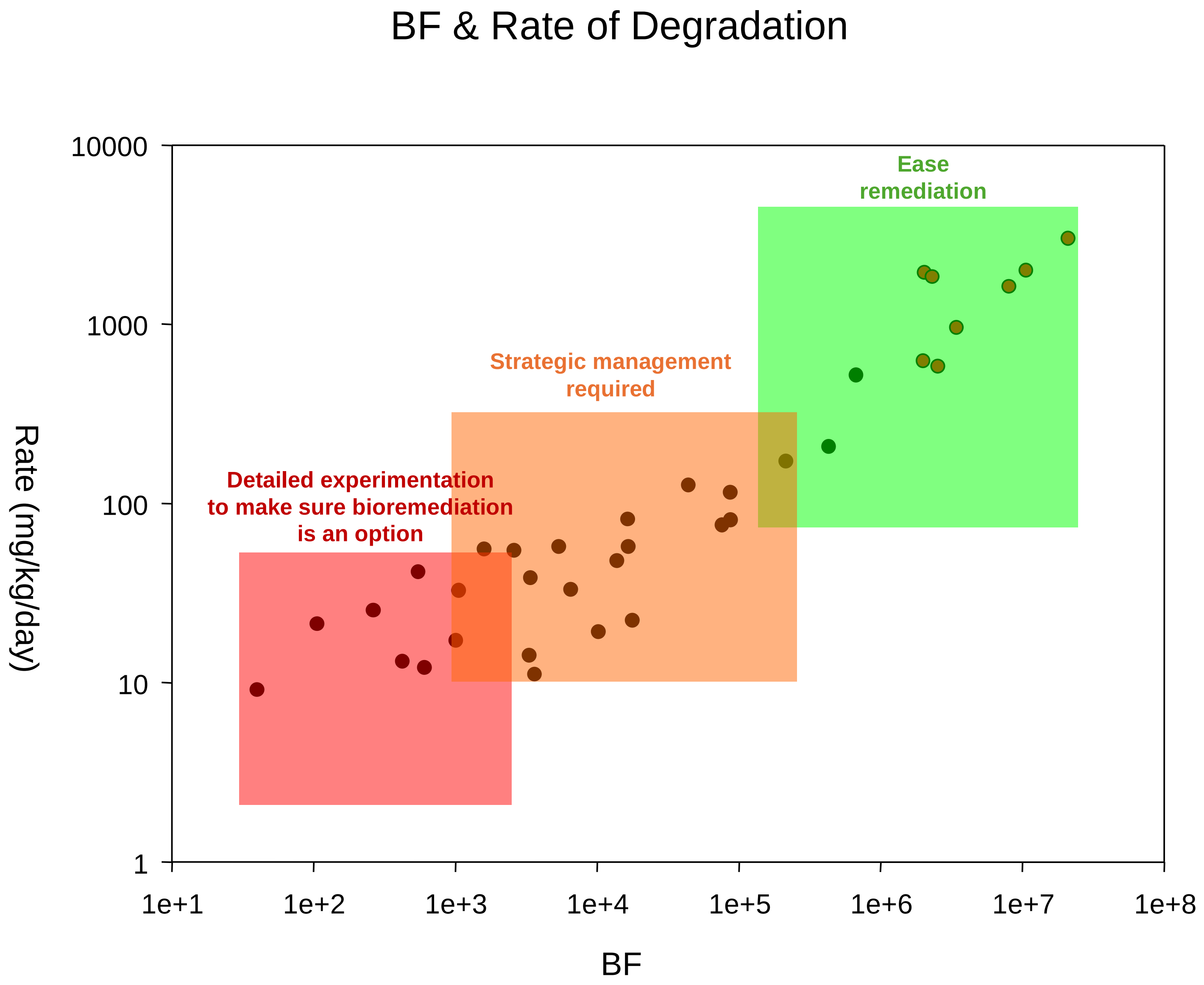




Only when all of the results (including **chemical, biological, toxicological and microbiological** data) are compiled together, we can be confident that active bioremediation is taking place.

BF = bioremediation factor; I = induction; [TPH] = Total petroleum hydrocarbons concentration
MPN = most probable number ; Resp = respiration

Predicting remediation: the “Algorithm”

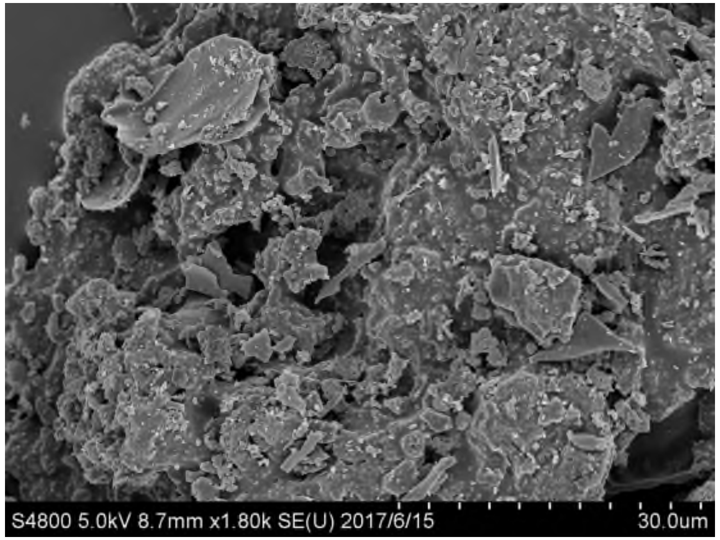


What are we still missing?

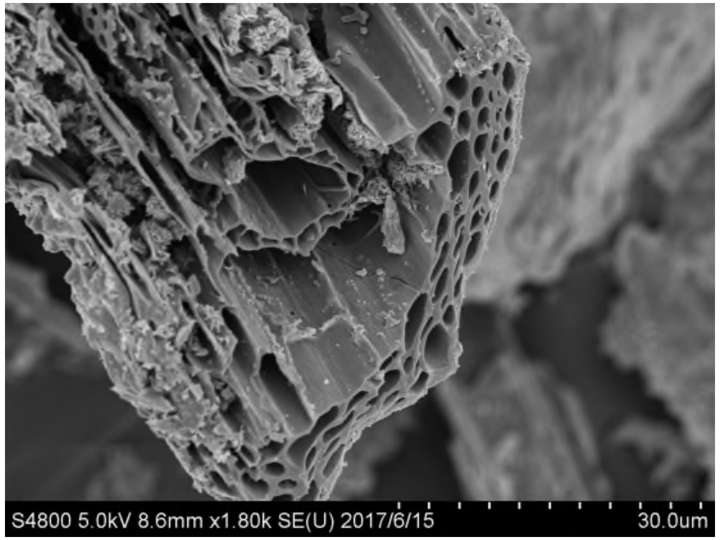
- Mechanisms of biochar-microbe interactions are poorly understood
- Match-making biochar with soil microbial degraders yields unpredictable outcome
- Can biochar alleviate the salinity effect on soil microbial community biodegradation activities?
- Can biochar provide us with the opportunity to increase sorption/decrease bioavailability of the chemicals, and increase surface contact of contaminants with the soil microbial community?

Field verification of low-level biochar applications

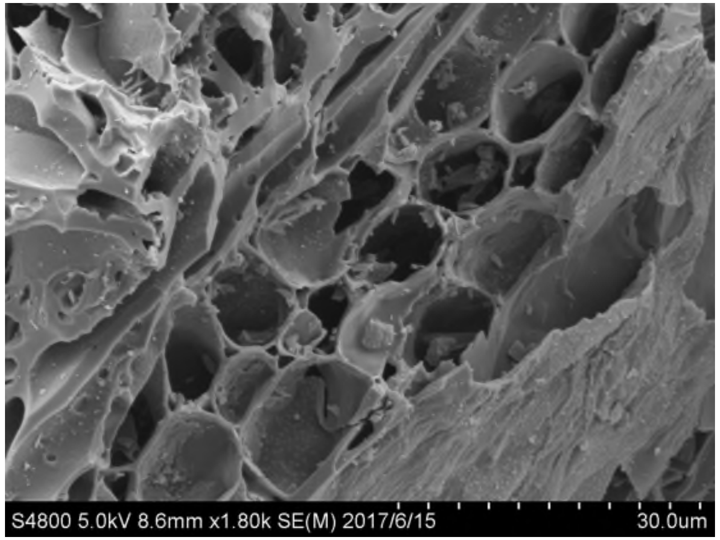
- To date little information and guidance on field-scale in situ applications of biochar.
- Field trial results are often inconsistent due to variable field conditions and contrasting biochar properties.
- Field experiment was conducted on an upland farm located in Zhouzai village, Zhangzhou city, Fujian province in southern China,
- Low level of [Cd] = 0.38 mg/kg (regulatory limit = 0.30 mg/kg in plants growing in contaminated soils)



Pig Manure Biochar (PMB)



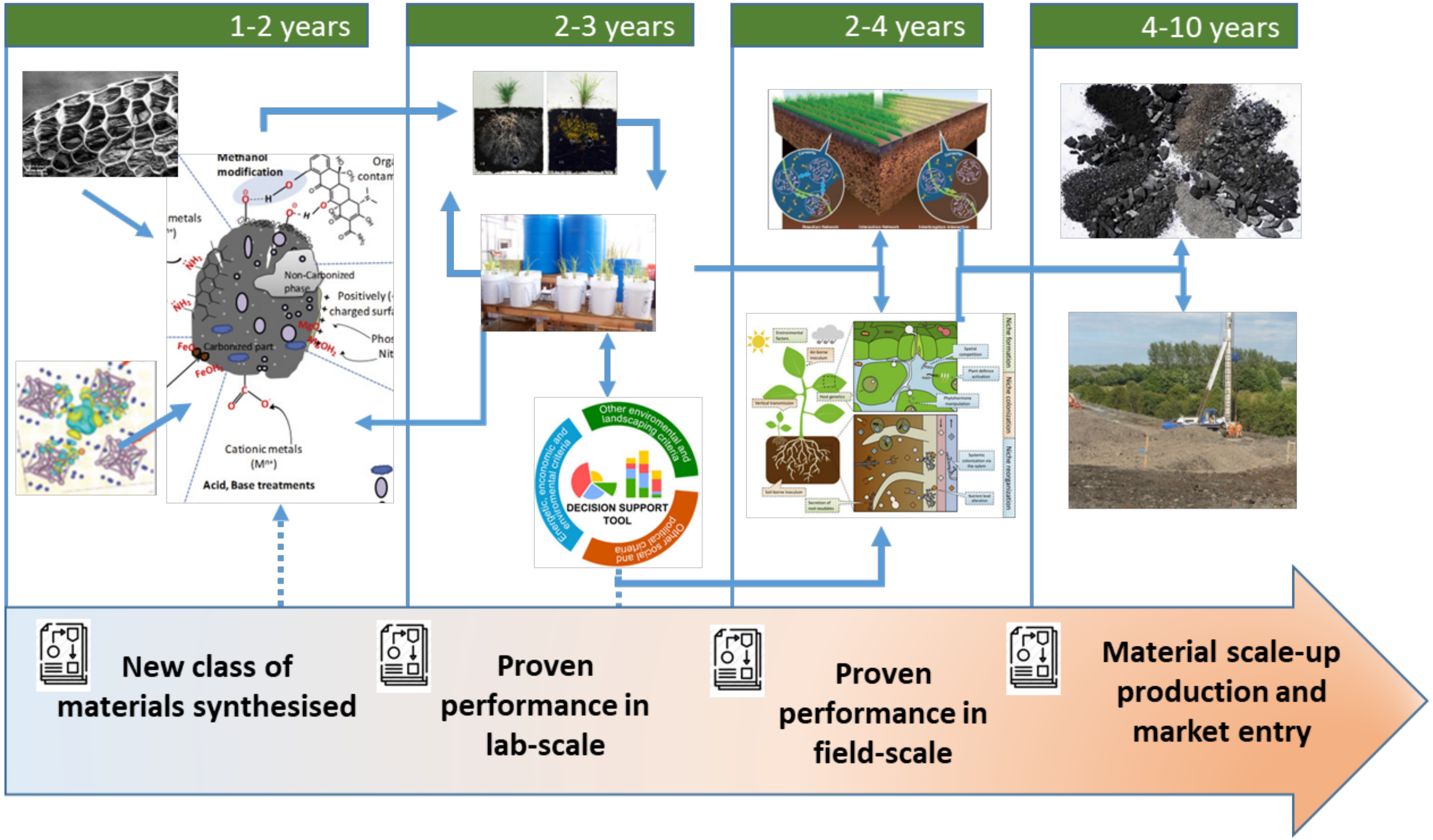
Rice Straw Biochar (RSB)



Rice Husk Biochar (RHB)

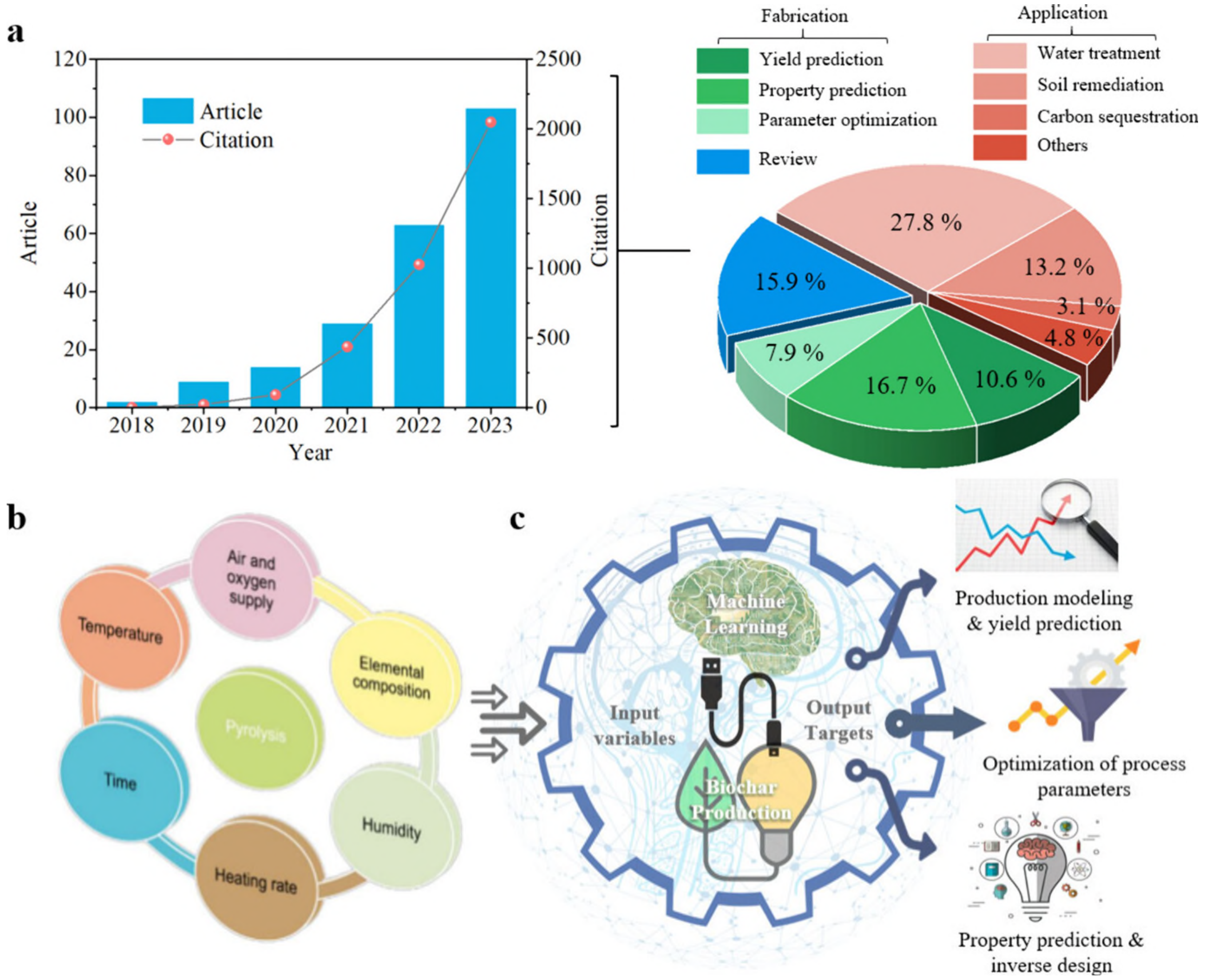
Zhang et al., 2023, Front. Environ. Sci., 10,1114335

So where are we and what is next?



Machine Learning toward realizing End-to-End Biochar Design for Environmental Remediation

Wang et al., 2024, ACS ES&T Engineering, doi: 10.1021/acsestengg.4c00267



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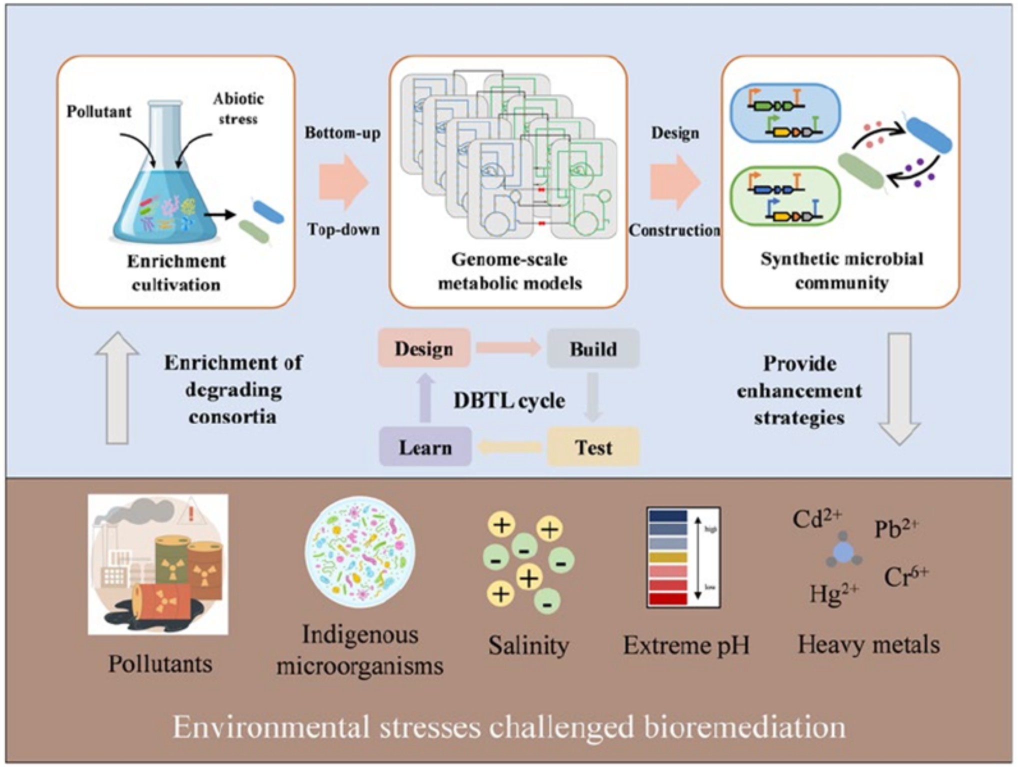
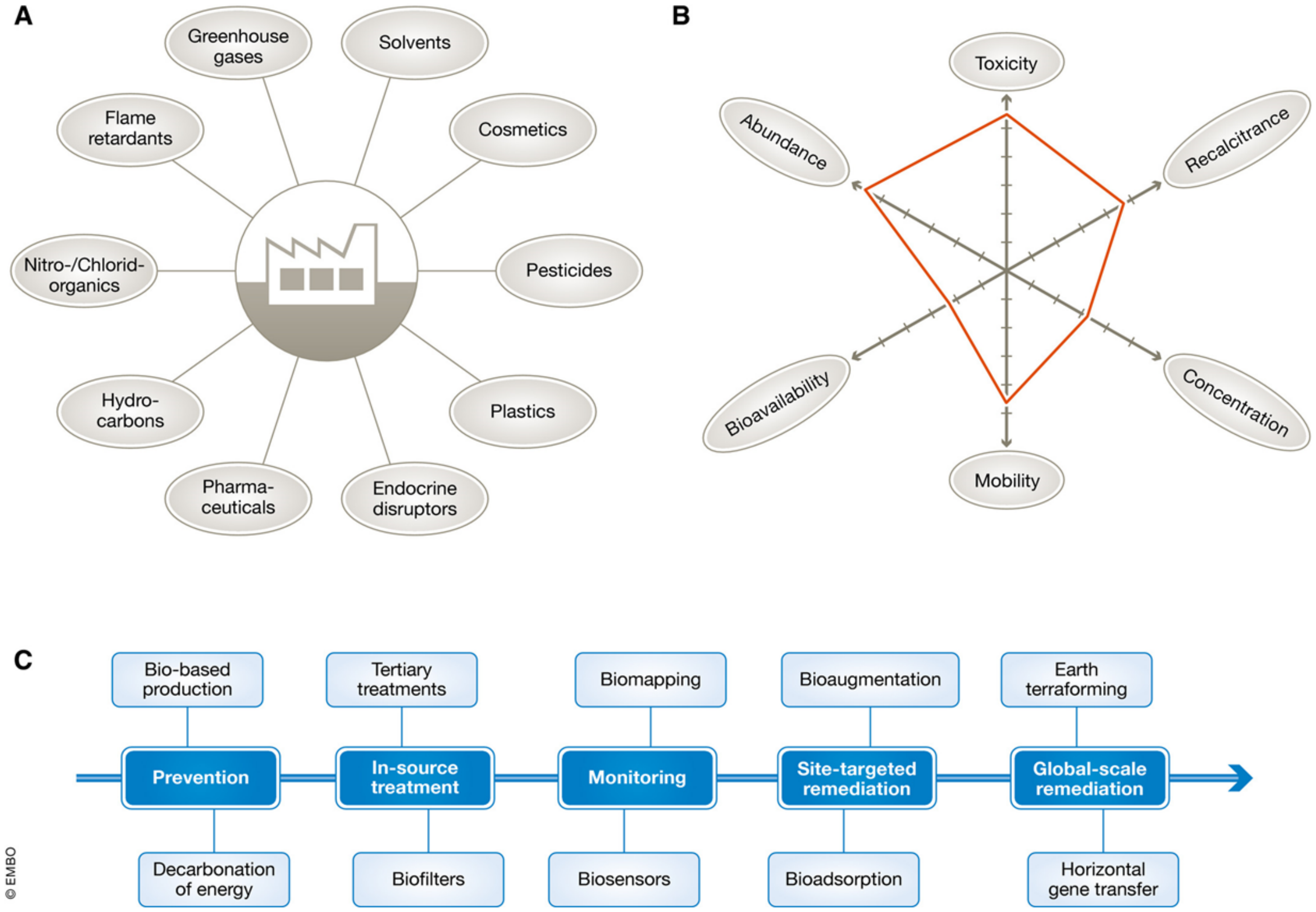
Advanced biotechnology for sustainable remediation



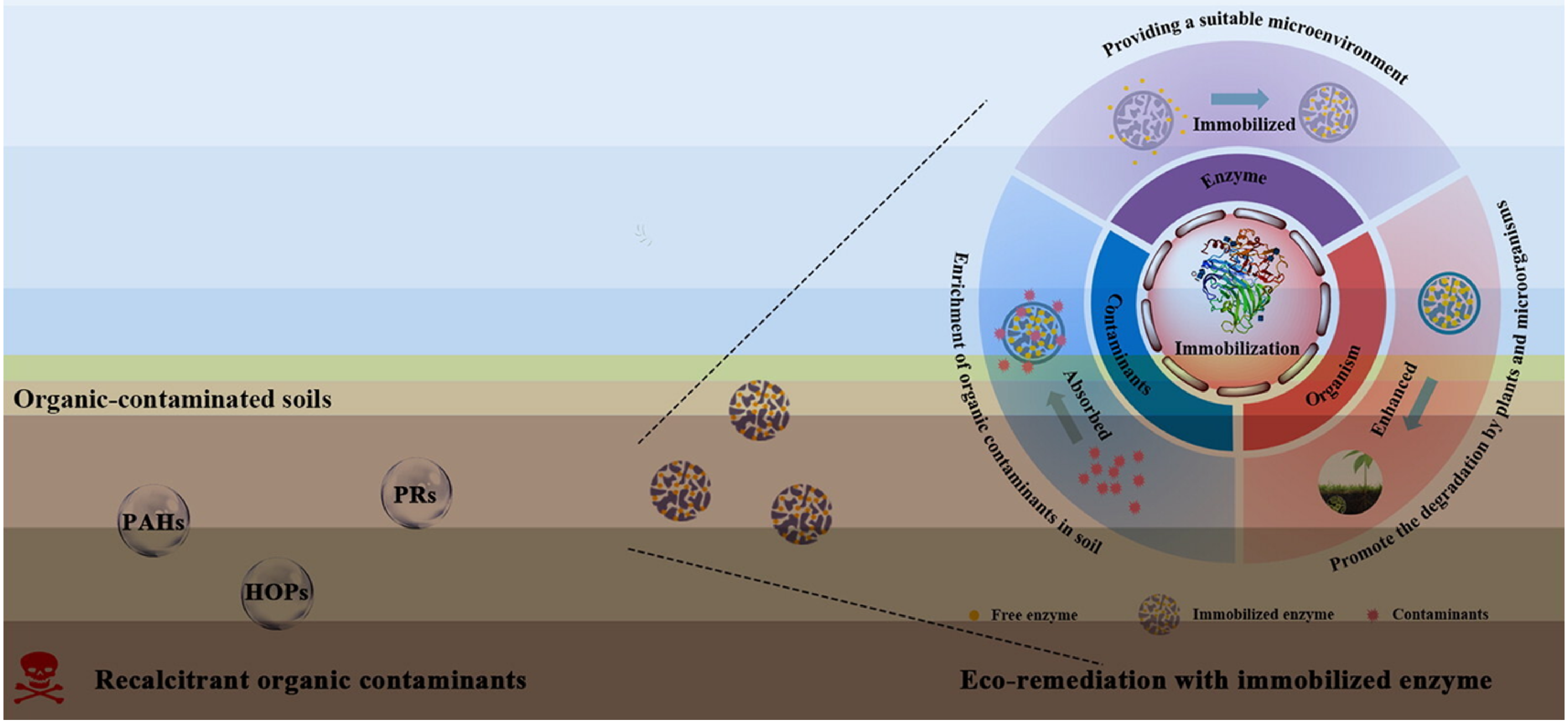
Synthetic microbial communities and metabolic modelling for bioremediation

Wang et al. 2023, CREST,
DOI: 10.1080/10643389.2023.2212569



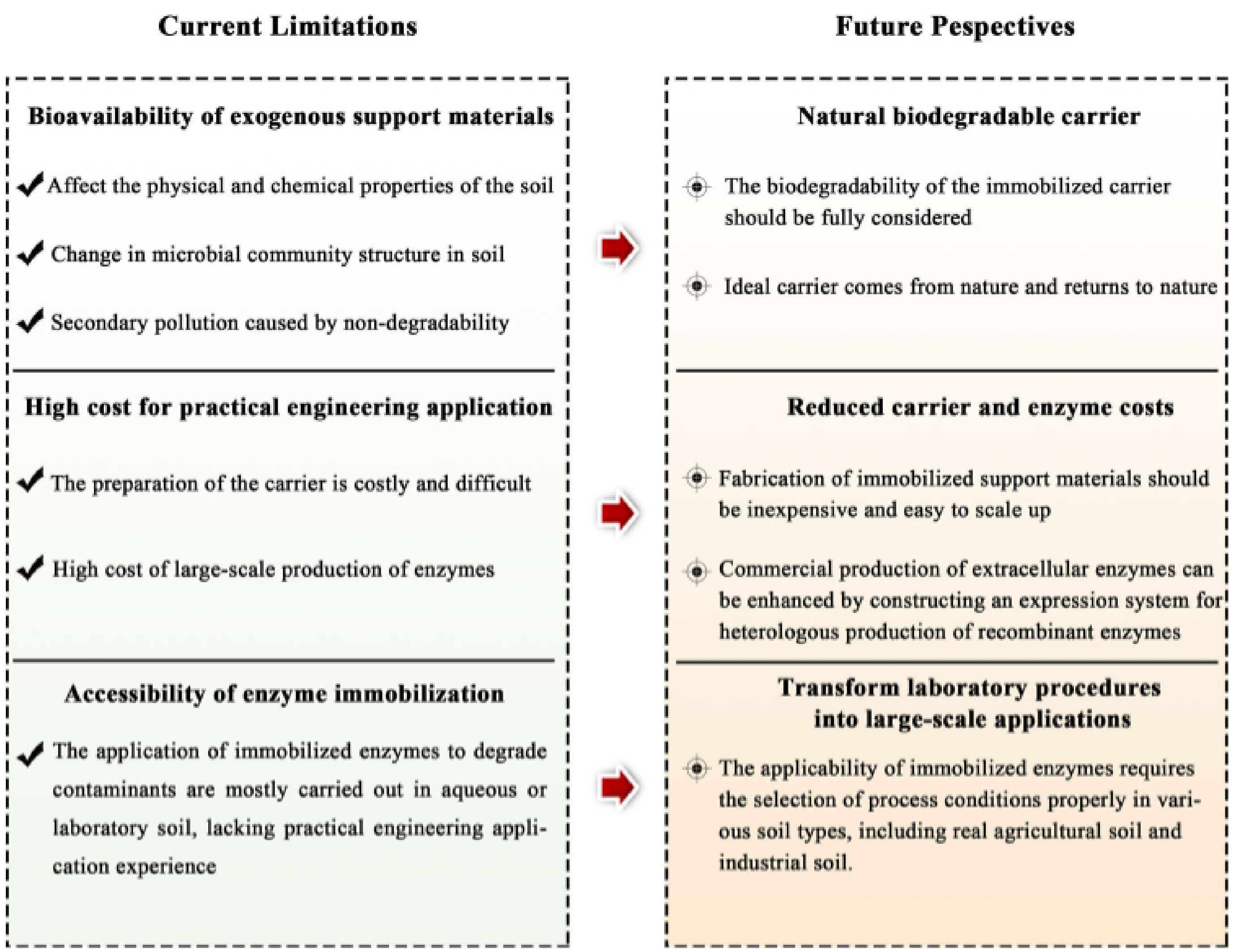
Lorenzo et al., (2018) EMBO Reports, 19: DOI: 10.15252/embr.201745658

Enzyme immobilization as sustainable approach for soil remediation

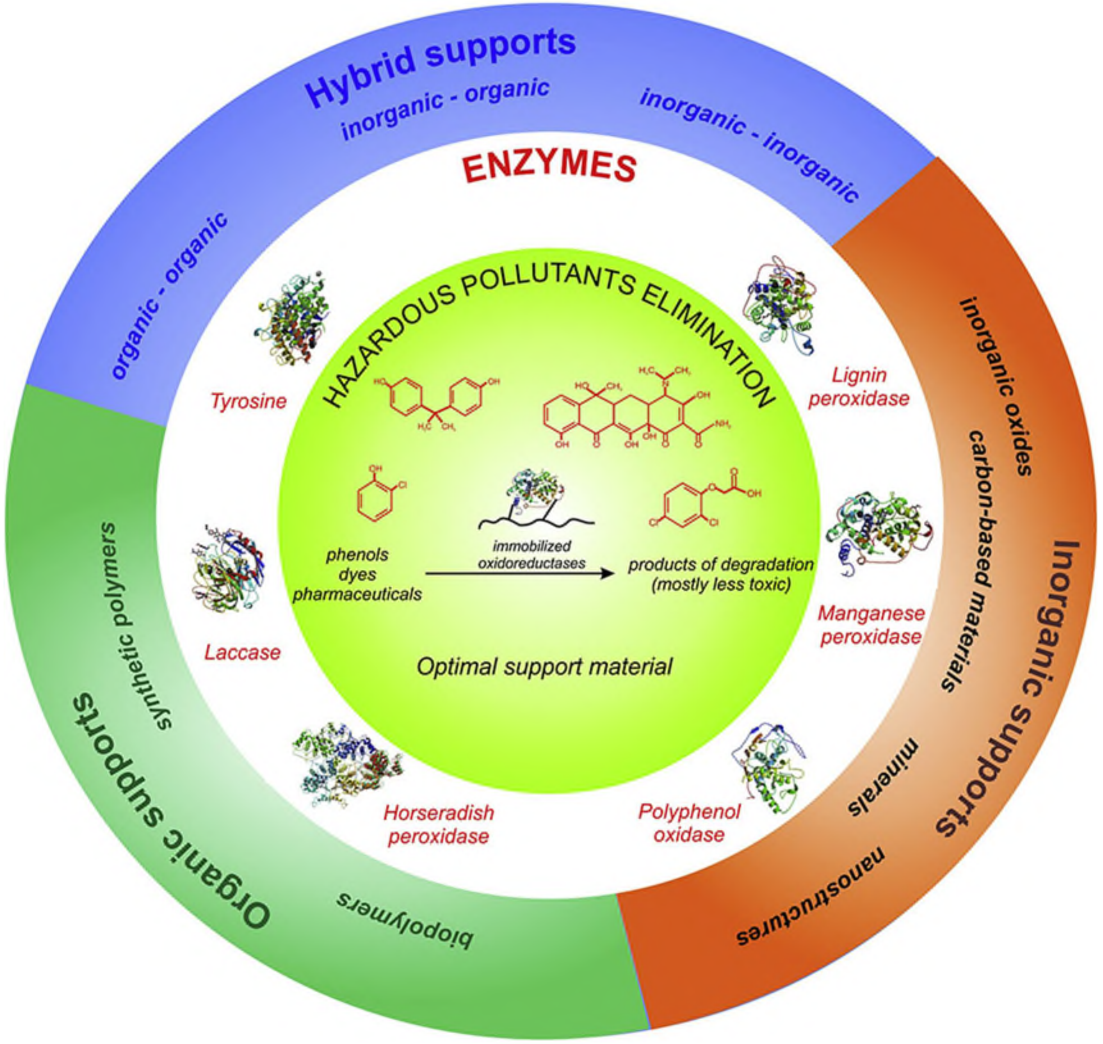


Wang et al., 2023, CREST, 53, 1684-1708

Current limitations and future perspectives of using immobilized microbial extracellular enzymes in practical engineering applications of organic-contaminated soils



Developments in support materials for immobilization of oxidoreductases



Organic materials

presence of numerous of reactive functional groups, high affinity for peptides, biocompatibility, limited negative effect on enzyme structure, abundant in nature

biopolymers: chitosan, alginates, cellulose, carrageenan, collagen, agar
synthetic polymers: ion exchange resins, polystyrene, polyamide, polyacrylonitrile

Inorganic materials

temperature and pH stability, mechanical resistance, operational stability, good sorption properties, inertness, easy surface functionalization, relatively cheap

silica, titania, alumina, zirconia, zinc oxide, magnetite, kaolin, hydroxyapatite, halloysite, active carbons, multi-walled carbon nanotubes, porous glass, noble metals

Hybrid and composite materials

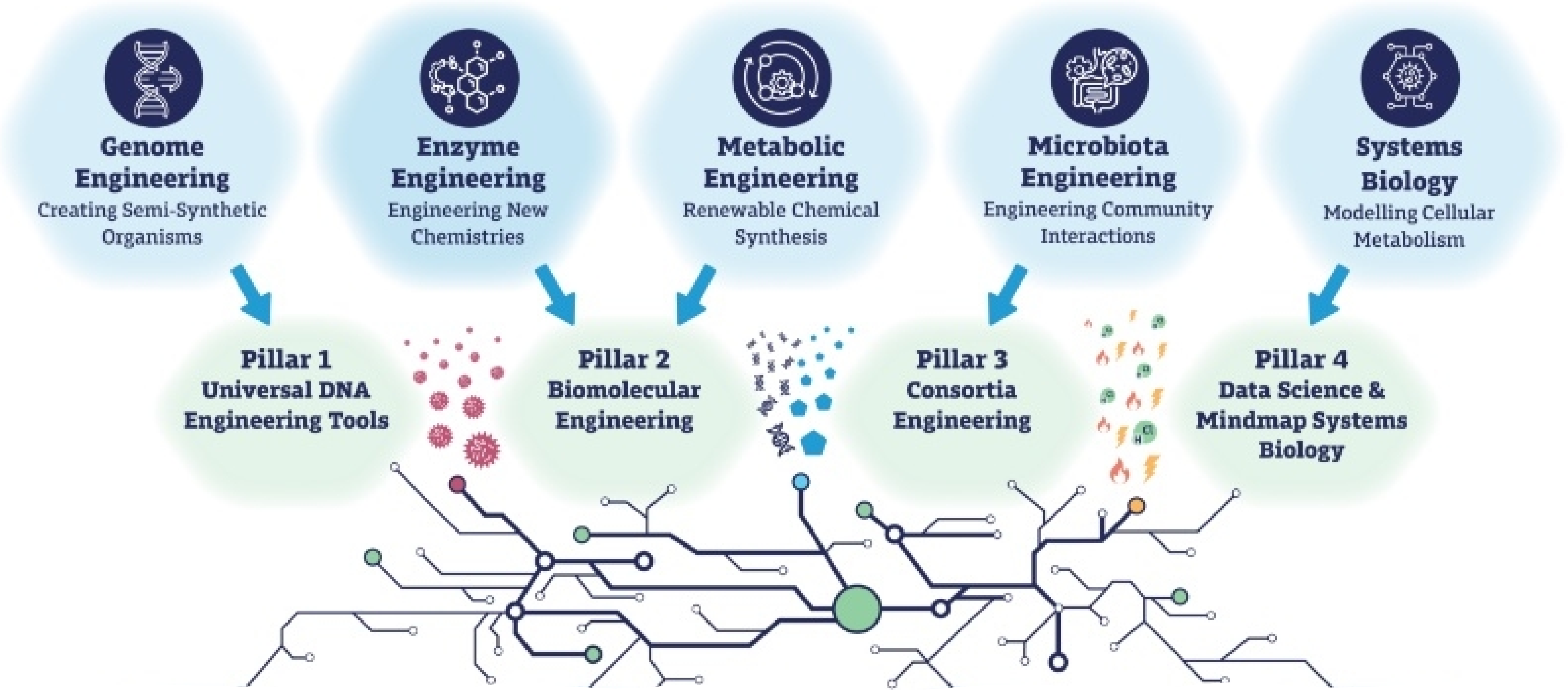
reusability of the matrix, strong binding of the enzyme, high stability, properties of the support material designed for selected enzyme and catalytic process

silica-magnetite, silica-zinc oxide, chitosan-silica, chitosan-clay, alginate-chitosan, polyamide-chitosan, polilactic-polyglycolic acid, polyvinyl alcohol-4-hydroxybenzaldehyde

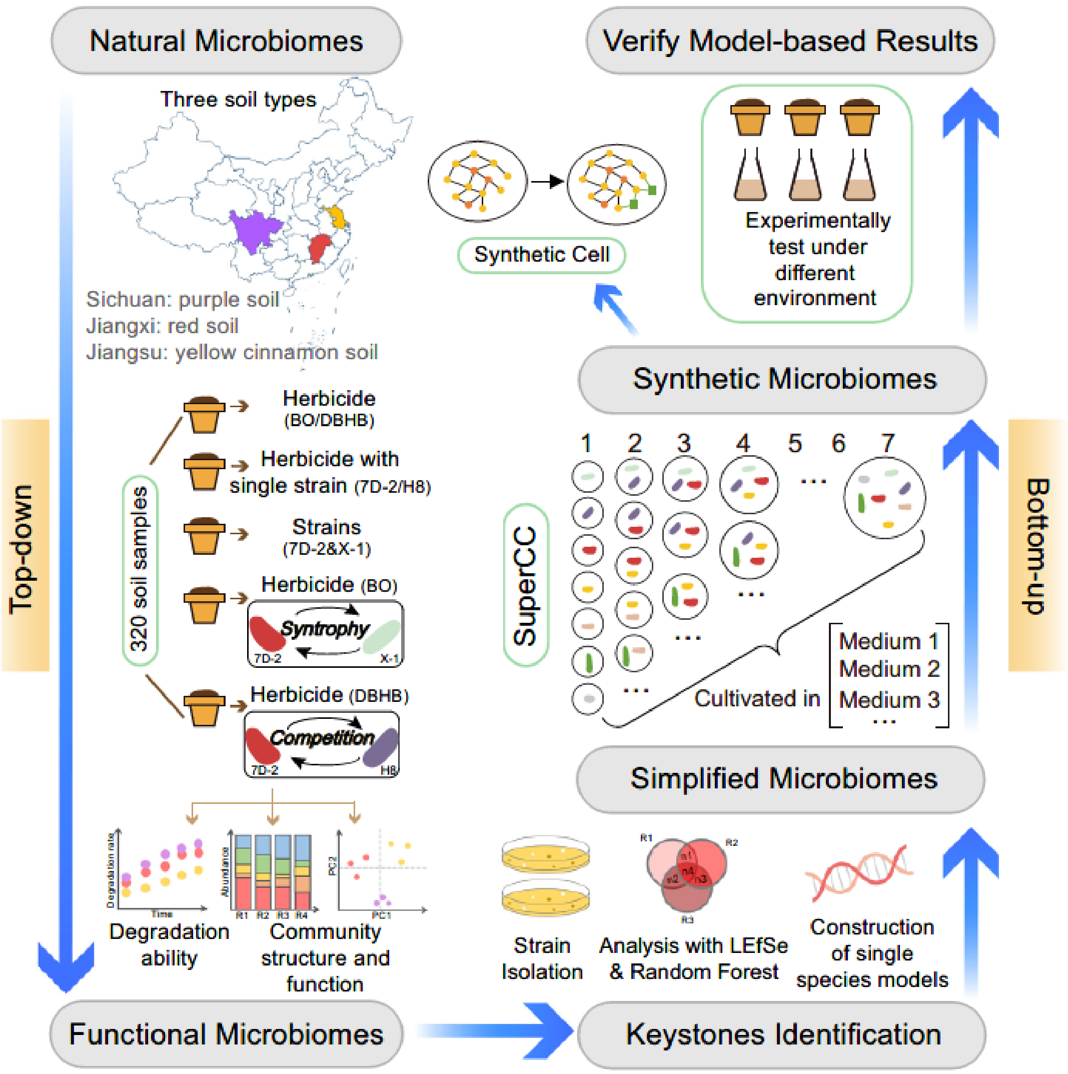
Zdarta et al., 2018, 258, 1-20

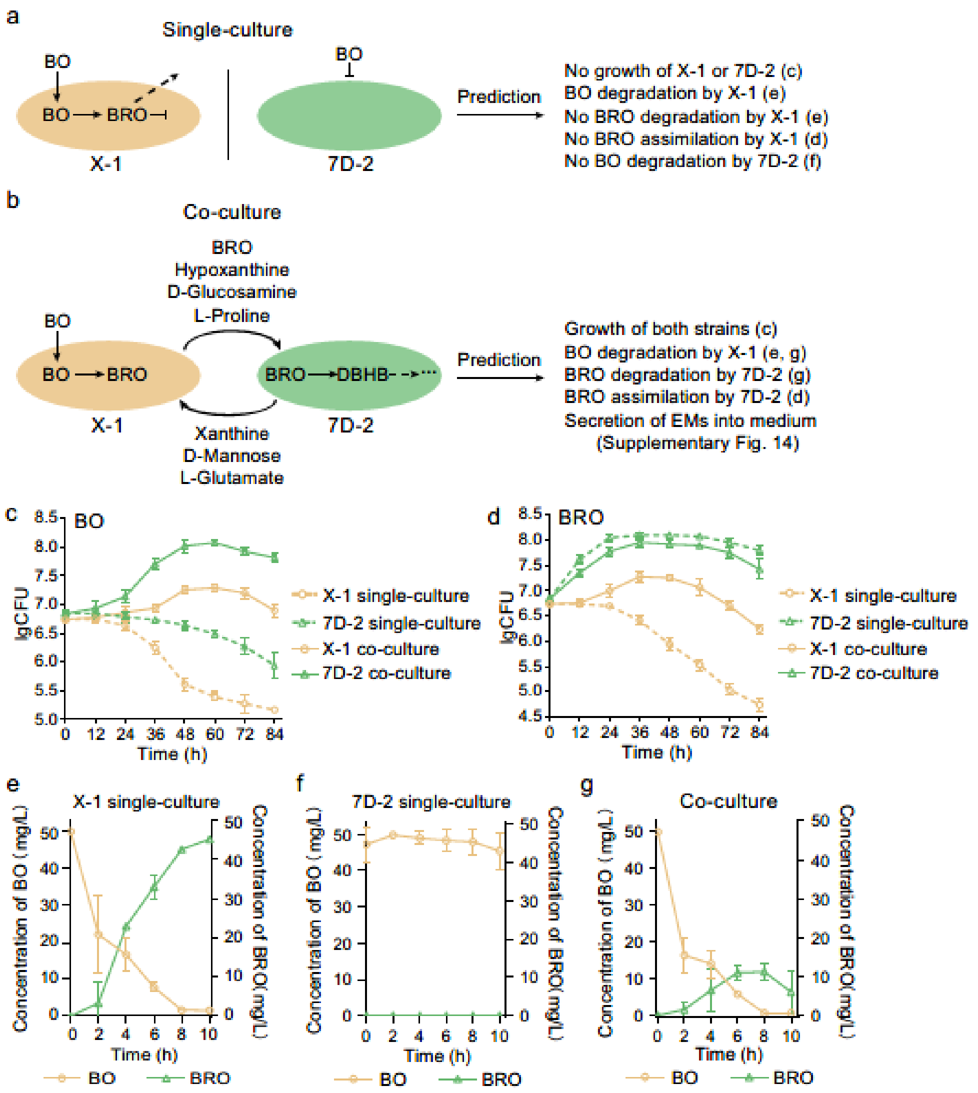
EBIC Environmental Biotechnology Innovation Centre

CORE COMPONENTS OF ENGINEERING BIOLOGY



Engineering natural microbiomes toward enhanced bioremediation by microbiome modelling





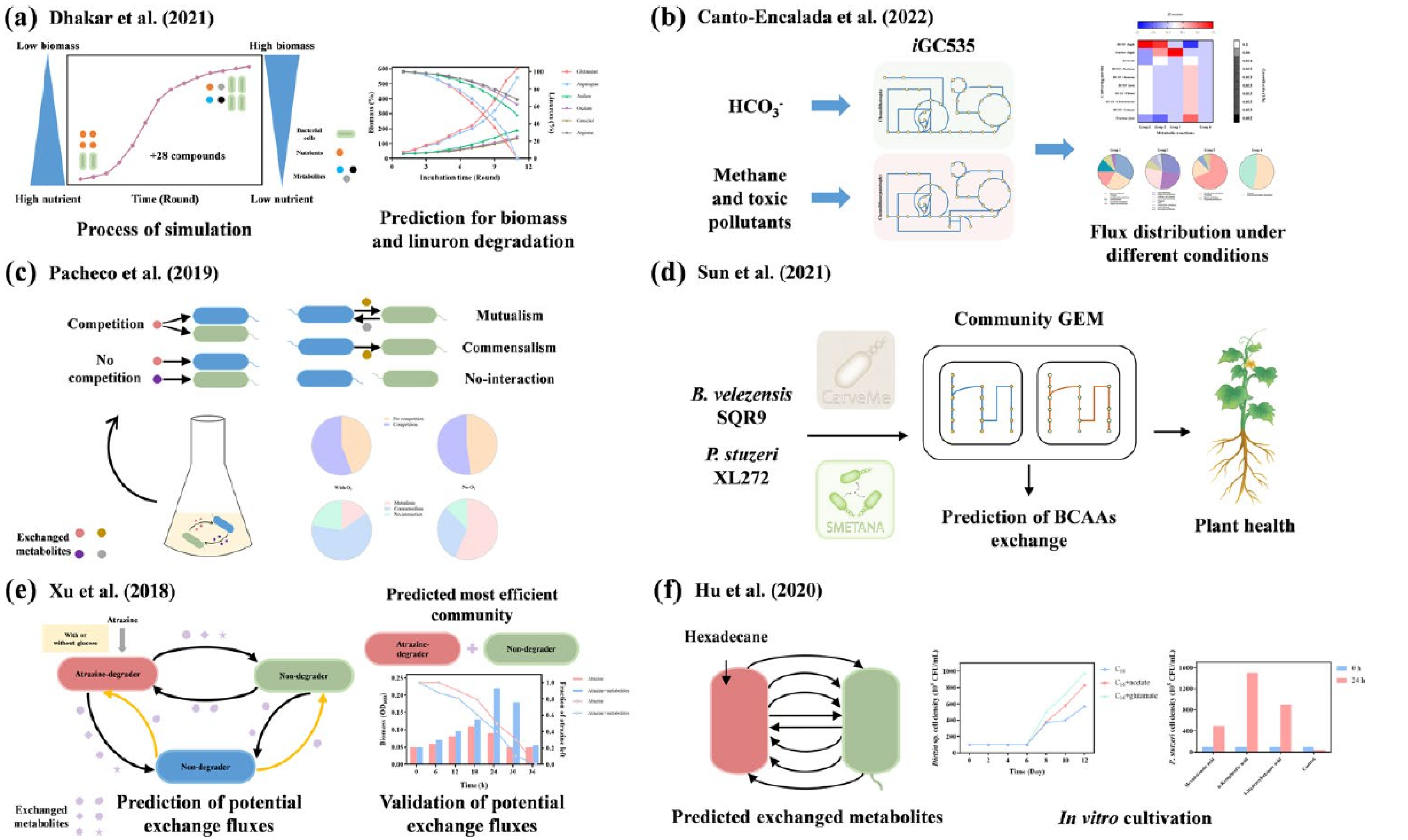
Ruan et al 2024, Nat Com, 15:4694

Applications of engineered bacteria for modelling microbial interactions and pollutant degradation

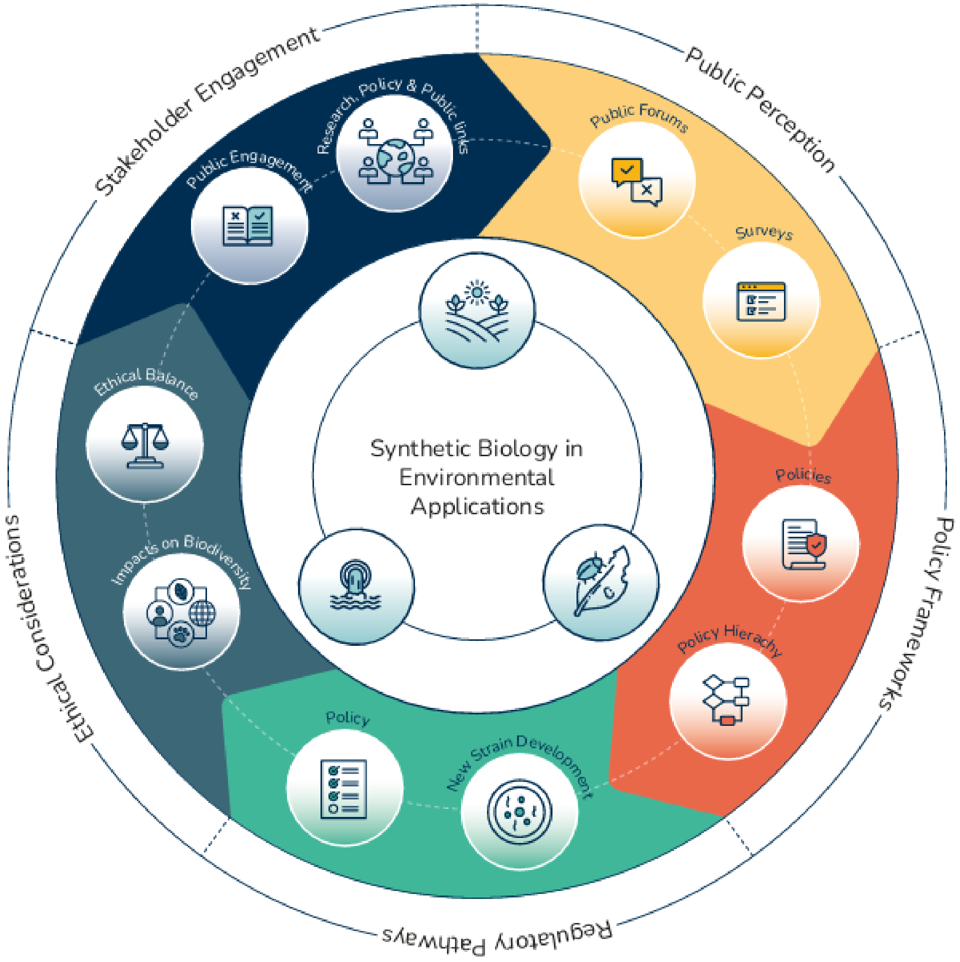
Single engineered strain biochemistry modelling for pollutant degradation

Applications of GEM for modelling microbial interactions

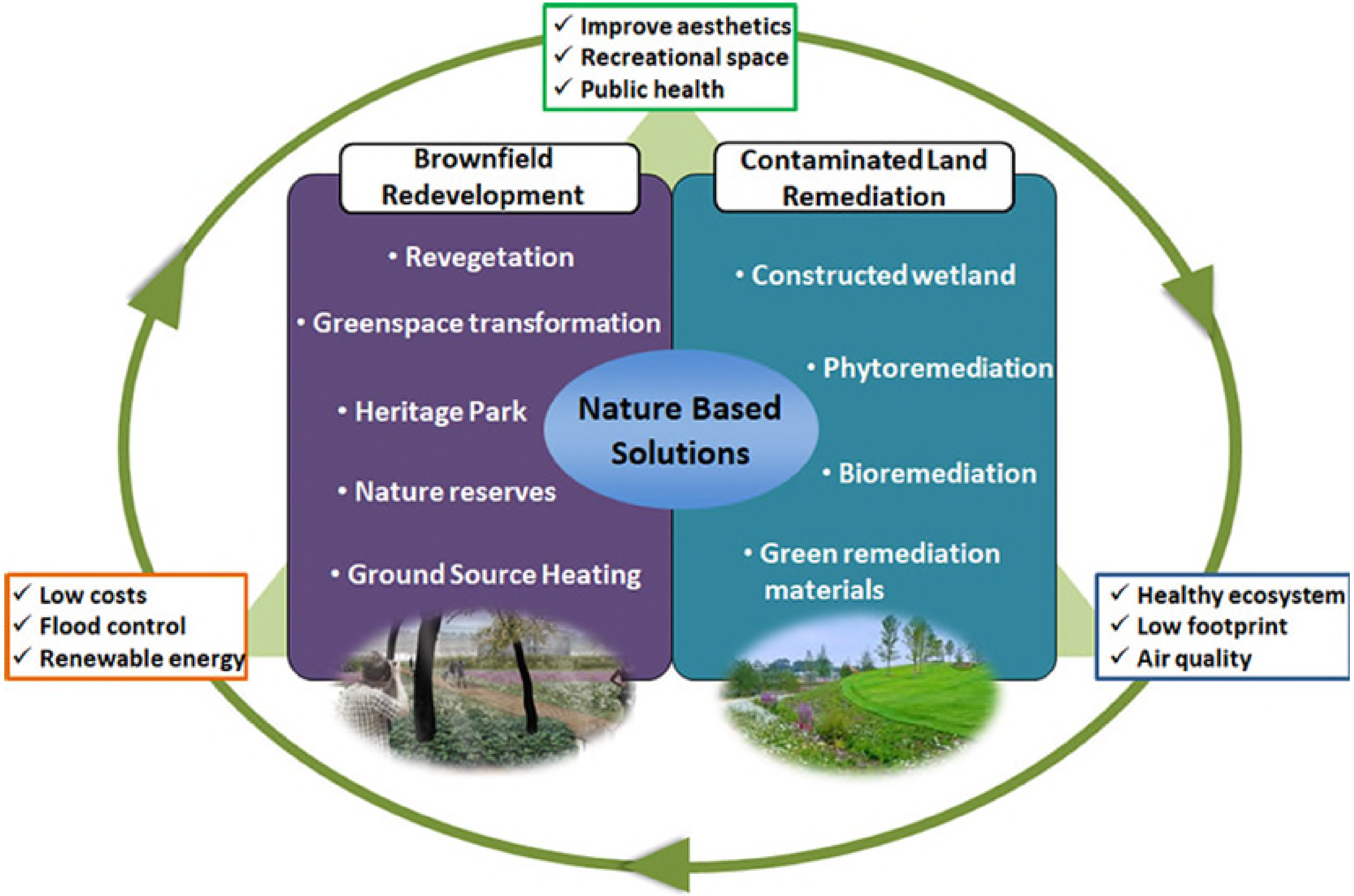
Applications of GEM for modelling microbial interactions in pollutant degradation



Challenges and opportunities for engineering biology for environmental applications



Nature based solutions for contaminated land remediation and brownfield redevelopment in cities

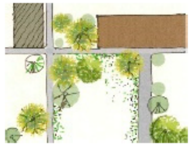
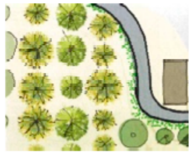
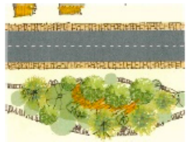
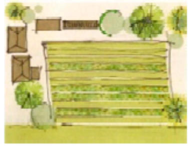
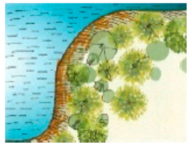
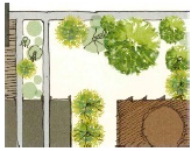
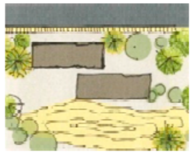
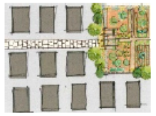


Song et al. 2019. STOTEN, https://doi.org/10.1016/j.scitotenv.2019.01.347

Green land use of brownfield

Green Infrastructure and Urban Biodiversity for Sustainable Urban Development and the Green Economy

(GREEN SURGE Project 2013-2017)

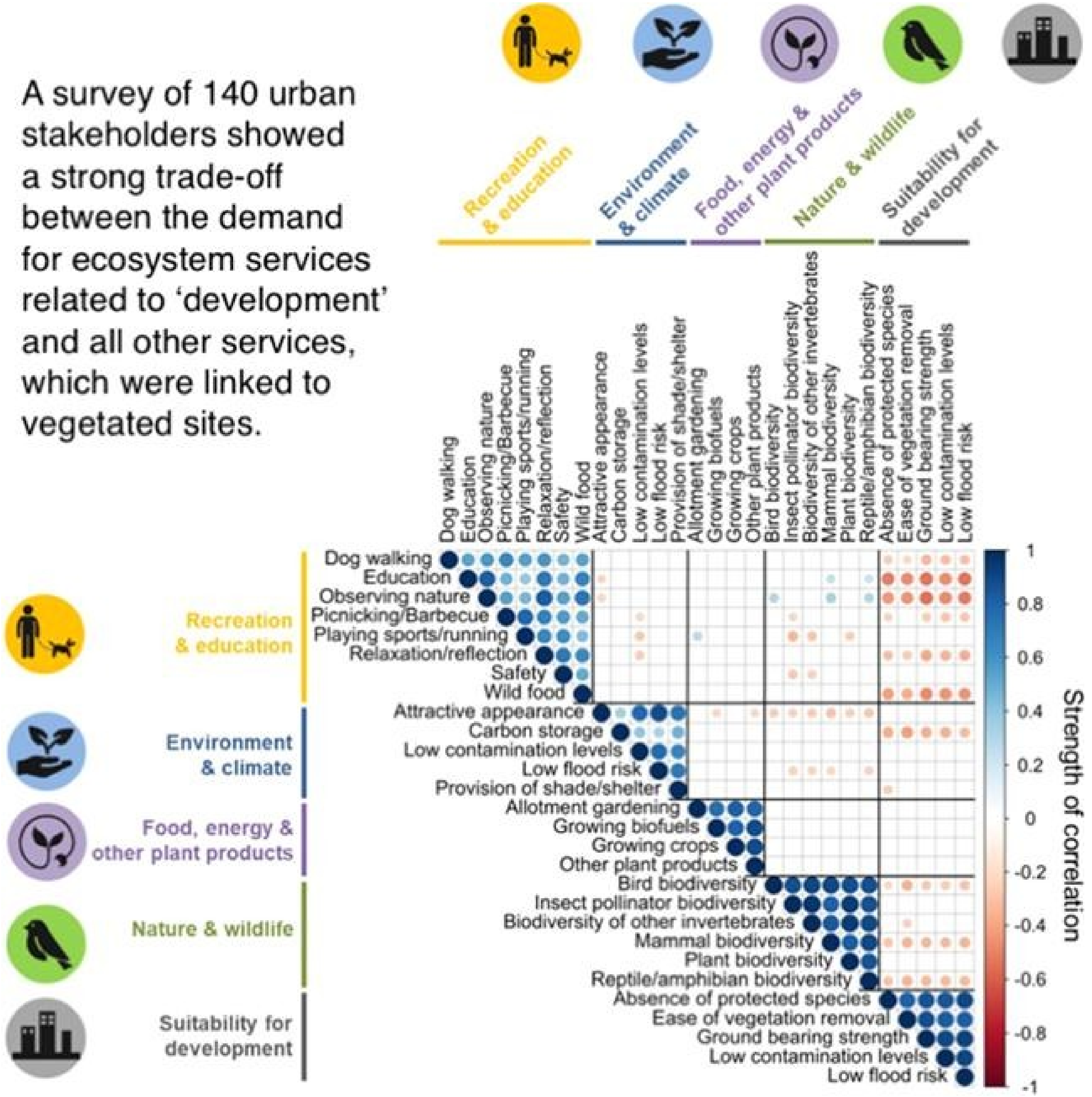
UGS Element	Image	Description	UGS Element	Image	Description	UGS Element	Image	Description
Building greenspaces		Plants on balcony/roof/façade or any place within a building.	Institutional greenspace		Green spaces surrounding public and private institutions and corporate buildings.	Biofuel production/ agroforestry		Land devoted to dedicated biofuel production, like short rotation coppice or poplar, etc.
Bioswale		Vegetated and gently sloped pit for filtering surface runoff.	Allotment		Small garden parcels cultivated by different people for non-commercial food production and recreation.	Horticulture		Land devoted to growing vegetables, flowers, berries, etc.
Riverbank green/ riparian vegetation		Greenspace along rivers, streams and canals, usually with foot or bike paths.	Community garden		Areas collectively gardened by a community for food and recreation.	Shrubland		Natural or secondary shrubland, e.g., heath, macchia, etc.
Historical park/ garden		Similar to large urban parks, but with distinct management due to heritage status.	Grassland		Pastures or meadows with grass cover.	Spontaneous vegetation on abandoned, ruderal, and derelict areas		Recently abandoned areas with spontaneously occurring pioneer or ruderal vegetation.
Neighbourhood greenspace		Semi-public greenspaces, vegetated by grass, trees, and shrubs in multi-story residential areas.	Tree meadow/meadow orchard		Fruit and nut trees, mixed agricultural use.			

Chowdhury et al., 2020, Sustainability, 12, 6278; doi:10.3390/su12156278

Trade-offs and synergies in the ecosystem service demand of urban brownfields

Washbourne et al. 2020. Ecosystem Services Volume 42, April 2020, 101074

A survey of 140 urban stakeholders showed a strong trade-off between the demand for ecosystem services related to 'development' and all other services, which were linked to vegetated sites.



Needs for the future of sustainable remediation

- **Governance Evolution**: Transition from outdated 19th-century governance structures to adaptive, flexible, and forward-thinking systems that address modern environmental challenges.
- **Modern Tools & Approaches**: Replace 20th-century tools with innovative 21st-century biotechnologies, integrating engineering biology, and environmental engineering to drive more efficient and sustainable remediation.
- **Digital Transformation**: Leverage advanced digital tools, such as AI, IoT, and data analytics, to improve decision-making, monitoring, and real-time responses to environmental changes.
- **User-Centric Solutions**: Develop remediation tools and systems that are intuitive, user-friendly, and accessible, encouraging broader participation and engagement from planners, managers, and citizens alike.

Needs for the future of sustainable remediation

- **Evidence-Based Practices**: Foster the adoption of remediation strategies that are grounded in scientific evidence, allowing for more informed and effective environmental interventions.
- **Adaptability to Change**: Design systems that are responsive to evolving environmental and societal needs, ensuring long-term sustainability in resource management and redevelopment.
- **Citizen-Centered Planning**: Emphasize the inclusion of community ideas and needs in planning processes, ensuring that future remediation efforts align with the values and expectations of the population.