Microplastic Pollution and Remediation Strategies: Challenges and Solutions

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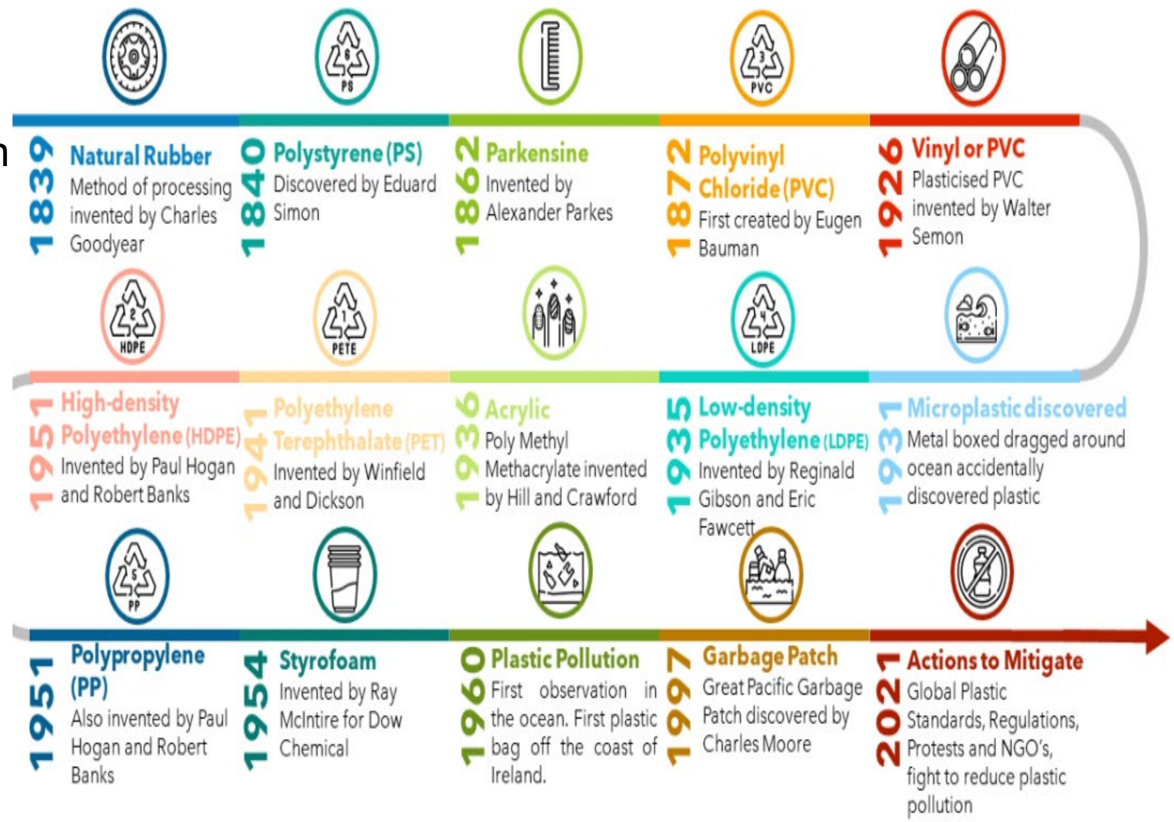
Introduction

- Researchers studying plankton first noticed plastic pollution in the ocean in the early 1930s. This was regarded as the first recorded incident of plastic pollution
- Nearly a century ago, Alexander Parkes demonstrated his invention “Parkensine” at the Great International Exhibition in London (1862). This moment in history marked the first production of a plastic material.



https://www.plasticcollective.co/history-of-plastic-production/

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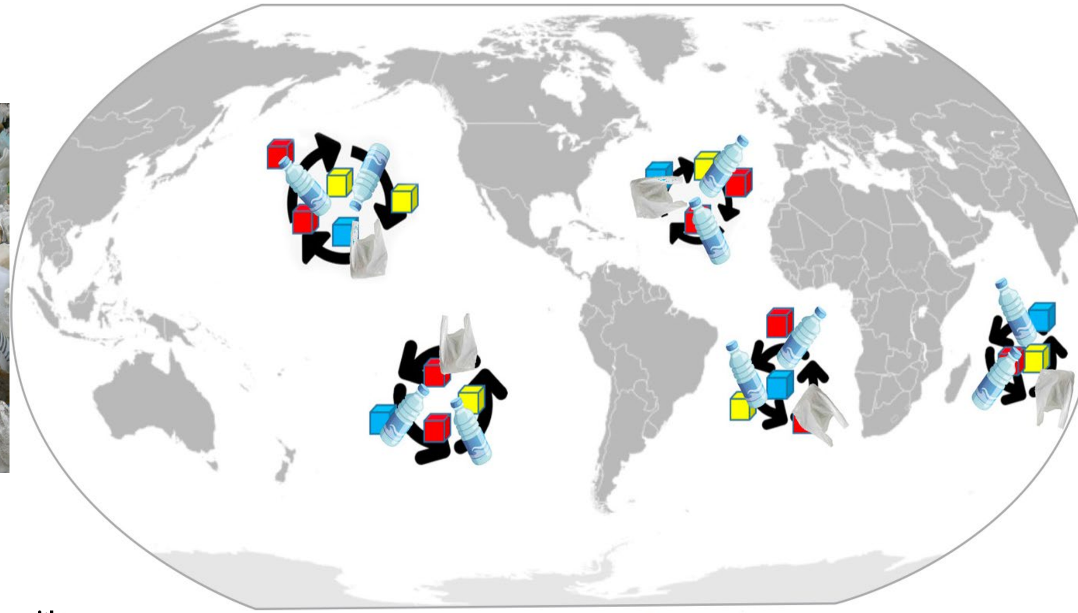
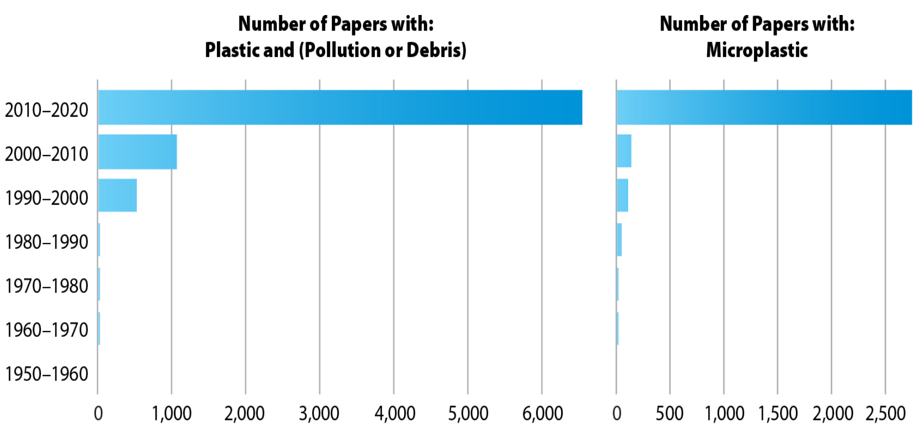
Plastic as an Environmental Issue?





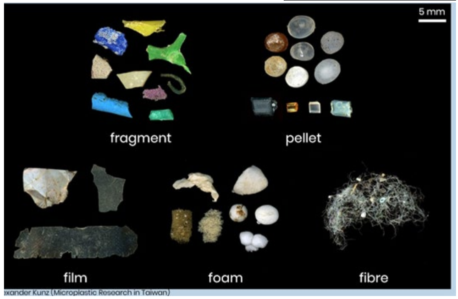
Thompson et al. (2004)

Characteristics of MPs

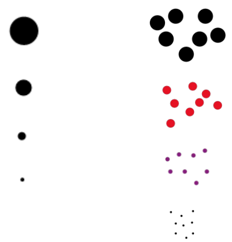
MPs (< 5 mm) → **Origin of MPs** ***Primary | Secondary***

Borah et al. 2022

Morphology (Shape)
Film | Fragment | Bead/pellet
Fiber | Foam



Size
< 5 mm

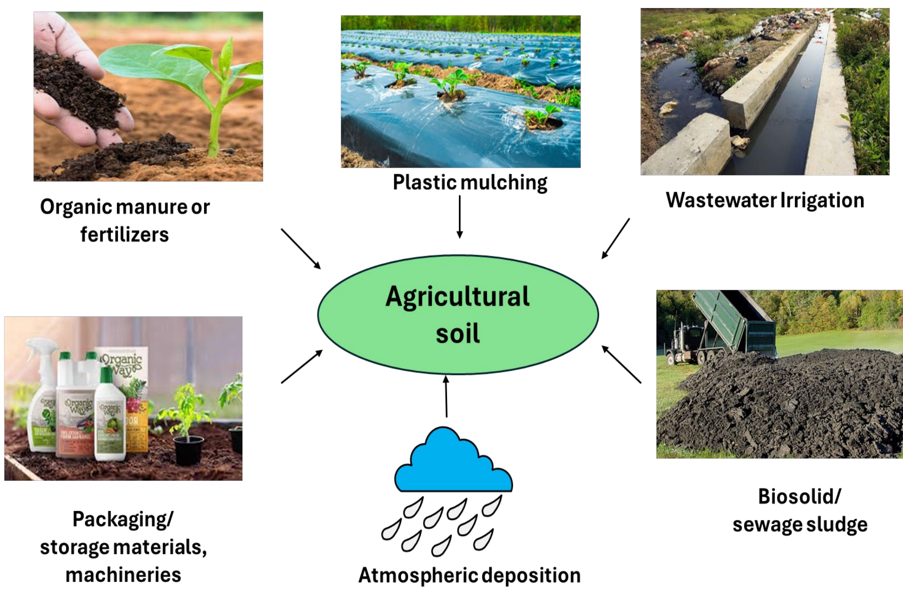


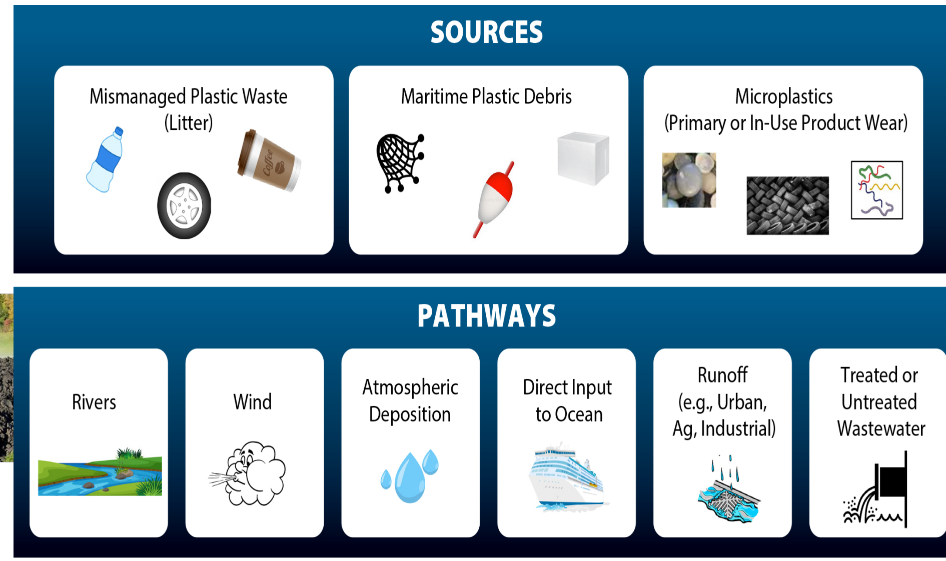
Chemical (Polymer)
PE | PP| PS | PVC | PET

Camensi *et al.* 2022

Borah et al. 2022

MPs entry into the Environment





https://tos.org/oceanography/article/the-story-of-plastic-pollution-from-the-distant-ocean-gyres-to-the-global-policy-stage

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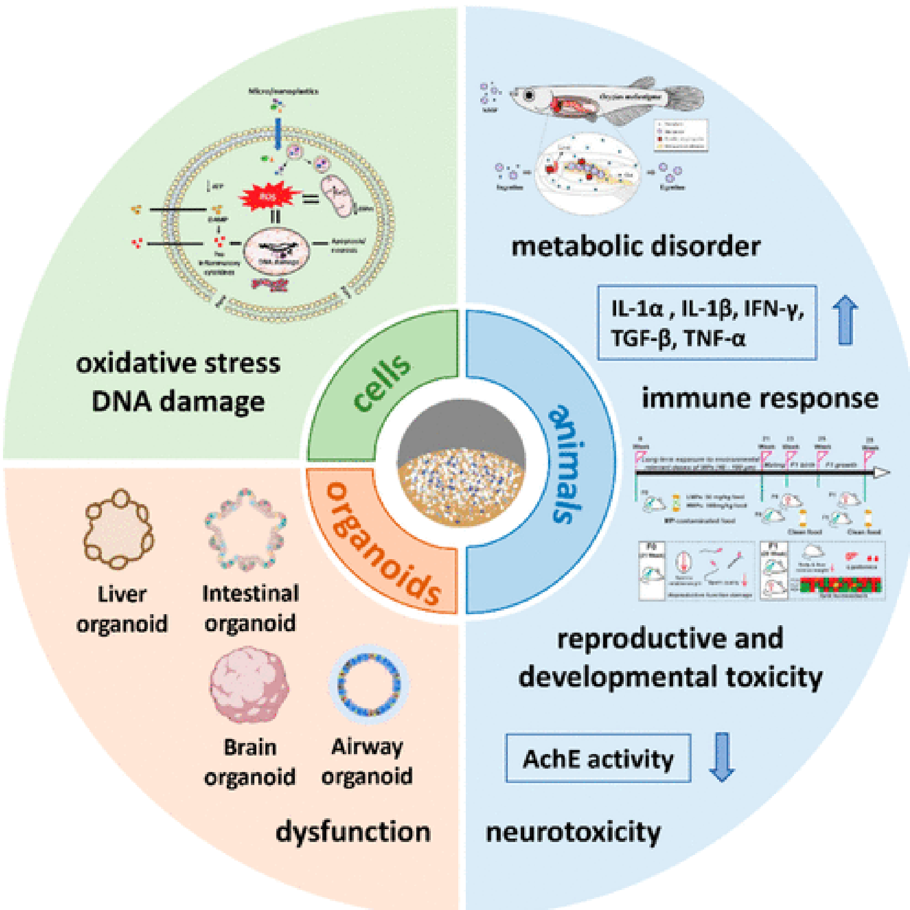
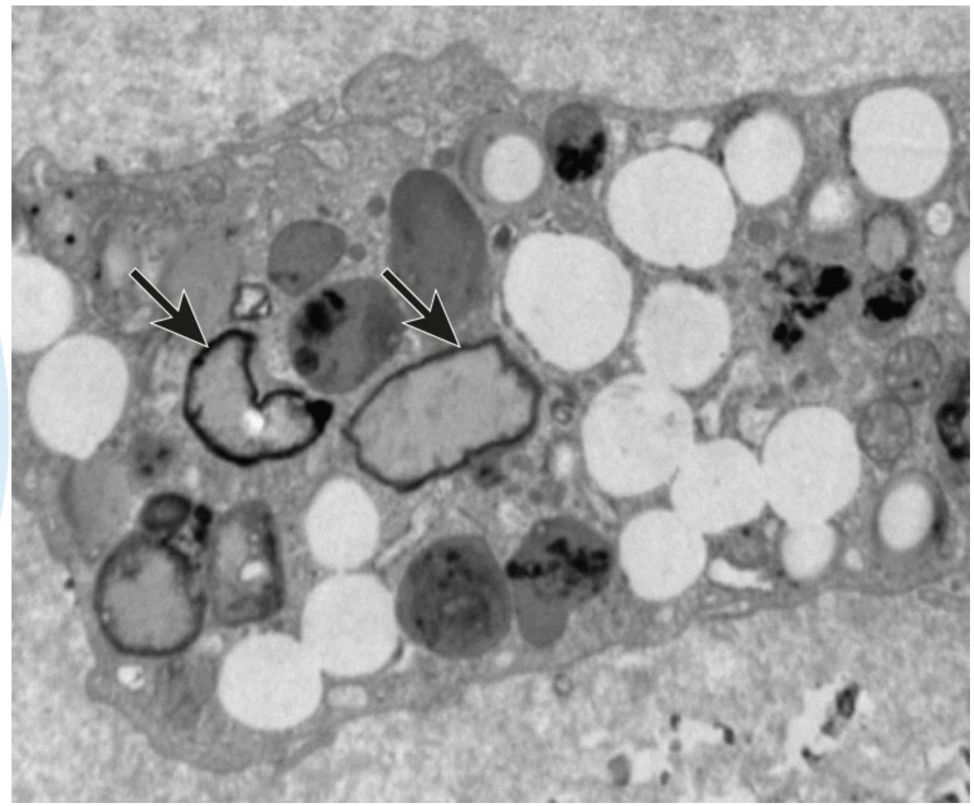
Impact of MPs on Environment and Human Health



Toxicity mechanism of microplastics.
Cells: oxidative stress and DNA damage
Organoids: dysfunction. Animals: metabolic disorder, immune response, neurotoxicity, as well as reproductive and developmental toxicity.
https://pubs.acs.org/doi/10.1021/envhealth.3c00052



Microplastic particles (arrows) infiltrate a living immune cell called a macrophage that was removed from a fatty deposit in a study participant’s blood vessel.

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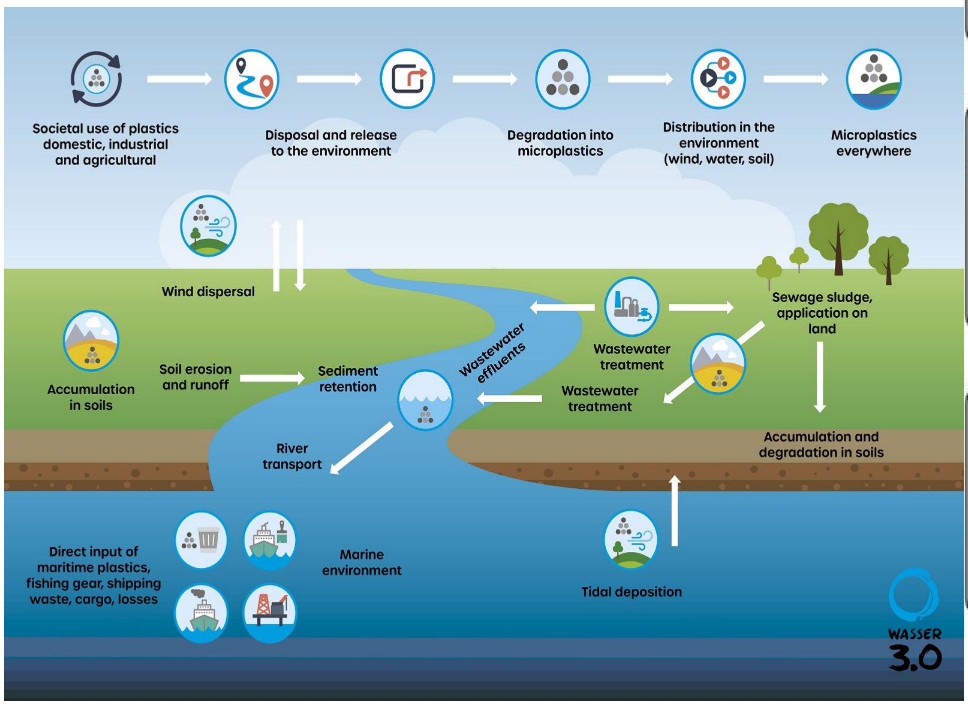
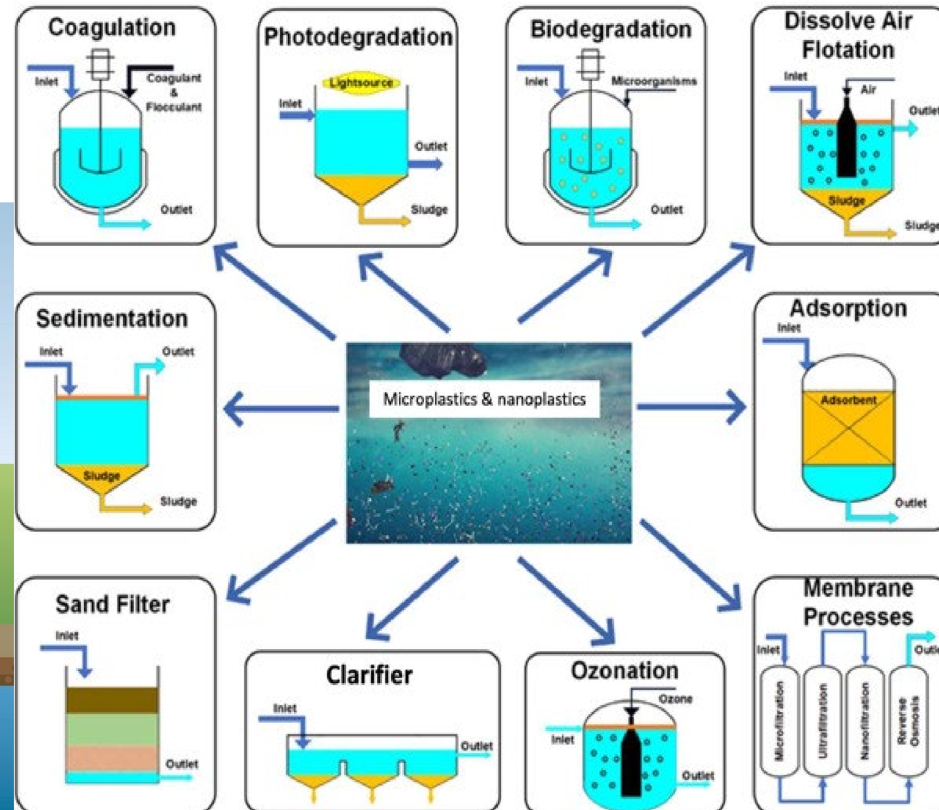
https://www.nature.com/articles/d41586-024-00650-3

Challenges in MPs Remediation

- Detection and quantification difficulties
- Heterogeneity of microplastics
- Persistence in the environment
- Economic and technological barriers





https://wasserdreinull.de/en/knowledge/microplastics/

https://doi.org/10.1016/j.polymdegradstab.2023.110635

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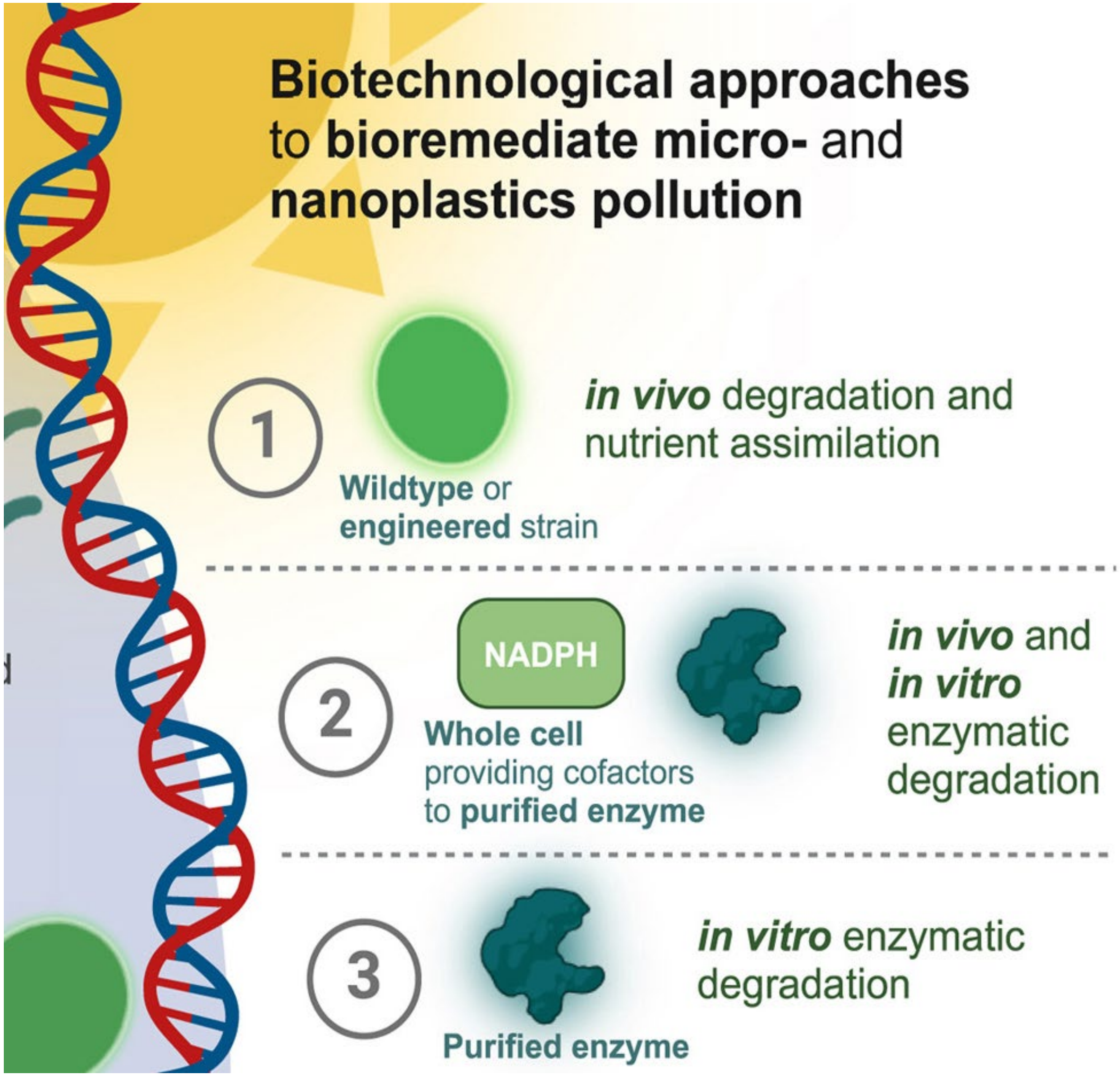
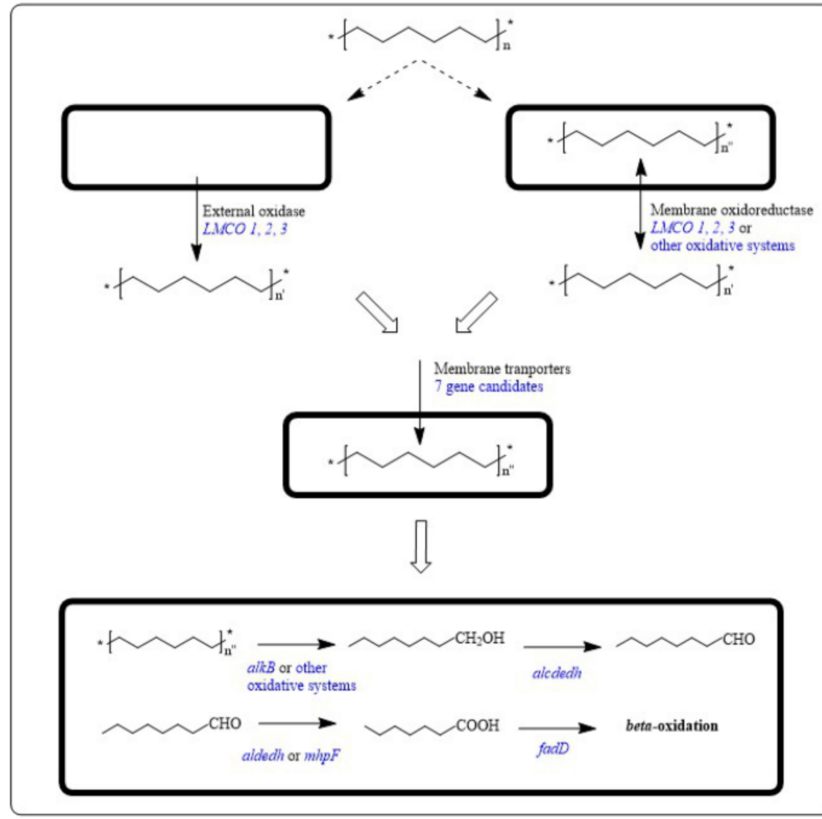
Biotechnological Approaches



Microbial Degradation

Barplots and map show data for metagenomic sample locations and associated material types.
Red dots on map indicate metagenomic sample was assembled via the custom metagenomic pipeline, yellow dots indicate samples from Zheng et al. biofilm study which were not assembled, but metagenome assembled genomes were instead taken from the OceanDNA catalog for the sample.
Bottom area shows information about the plastisphere data which was collected from the literature.

https://doi.org/10.1038/s41598-024-59279-x



Proposed metabolic pathways of R. opacus R7 for polyethylene degradation.
https://doi.org/10.1038/s41598-021-00525-x

Biotechnological catalysts for the biodegradation of polyethylene-based plastics.

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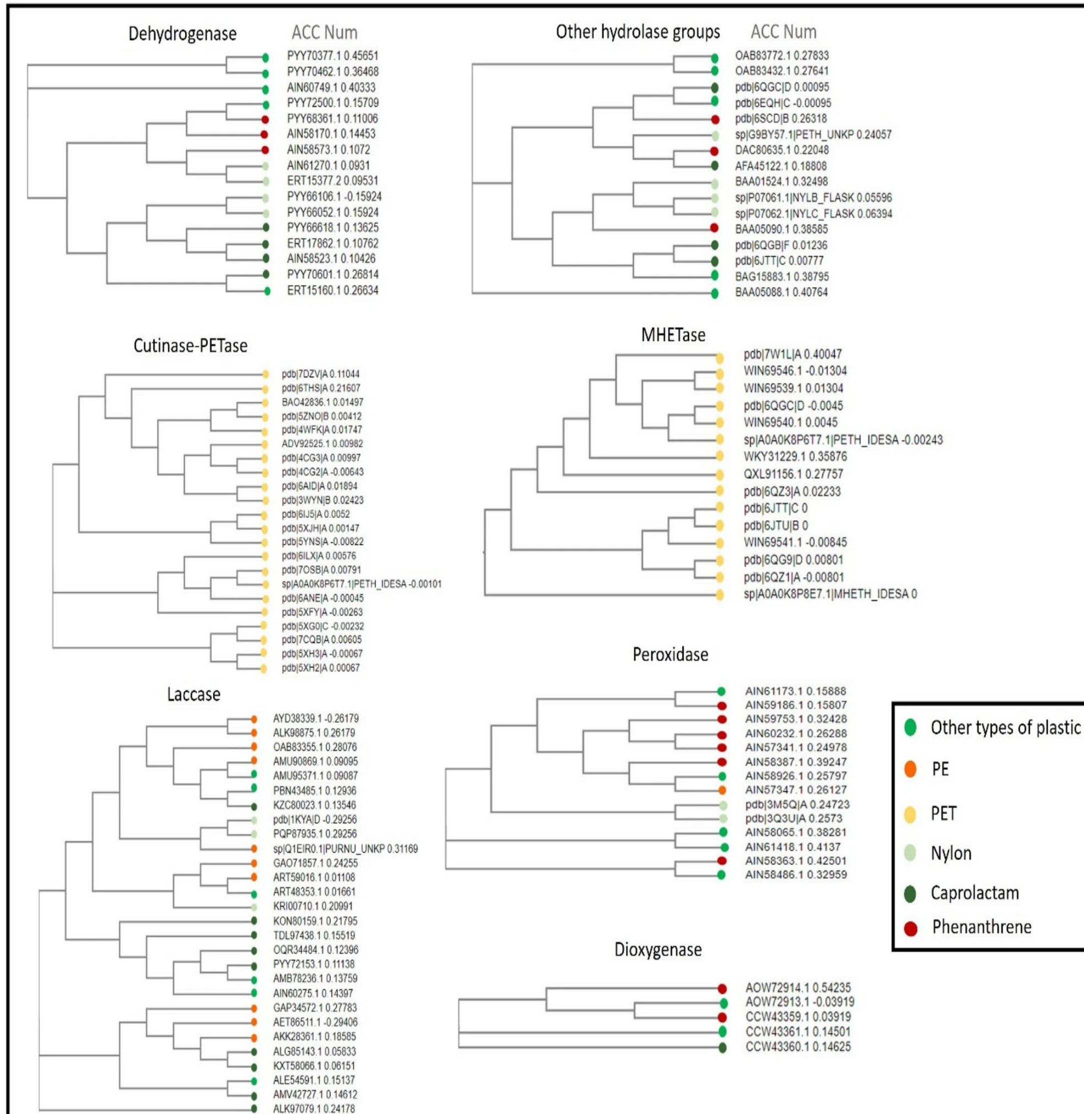
Enzyme-based Technologies

The depicted trees graphically elucidate the evolutionary connections among key plastizymes, encompassing the degradation of PE, caprolactam, nylon, PET, and phenanthrene, all within the framework of the comprehensive plastic-contaminated environment catalog (PDEC)



https://doi.org/10.1038/s41598-023-43042-9

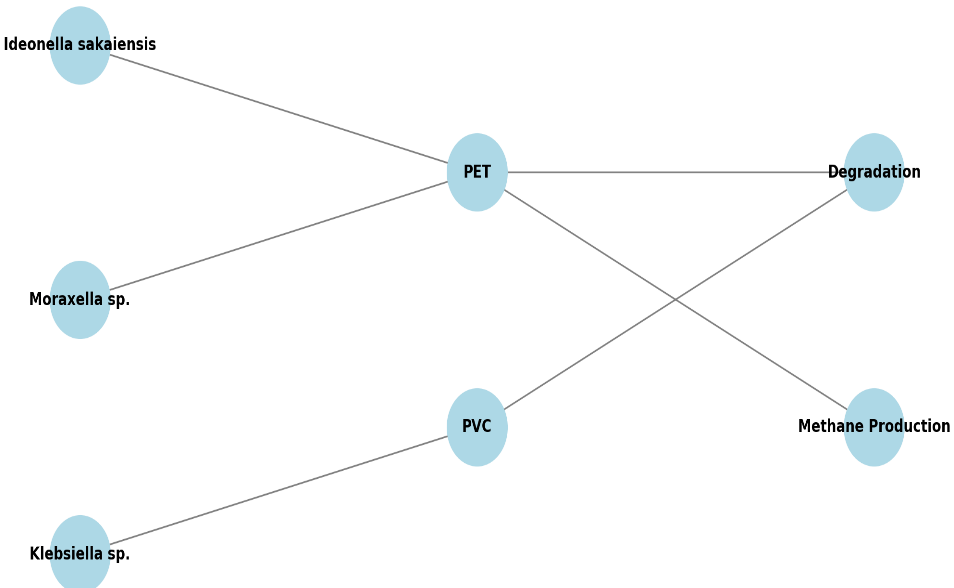
Case Studies

Organism	Polymer	Experimental conditions	Outcome
Ideonella sakaiensis	PET	Isolation from field samples	Degraded amorphous PET at ambient temperature and assimilation of its degradation monomers due to PET hydrolase (IsPETase)
Moraxella sp. Strain and Oleispira antarctica	PET	Isolation from the Antarctica environment	PET degradation at ambient temperatures (25 °C)
Pseudomonas and Bacillus consortium	PET	Isolated from petroleum-polluted soils	PET degradation
Klebsiella sp.	PVC	Larva's gut microbiota from Spodoptera frugiperda	Depolymerization and utilisation of PVC as sole energy source
Enterobacter	PHB	Mesophilic conditions	Methane production from PHB
Cupriavidus			
Moorella	PHB, PLA	Thermophilic conditions	Methane production from PLA
Tepidimicrobium			
Clostridium	TPS	Mesophilic conditions	Methane production from TPS
Rhodanobacter sp. Rs, Bacillus aryabhattai	PE	Inoculation on soil suspensions	Under co-culture, the ability for polyethylene mulching film degradation
Pseudomonas pseudoalcaligenes	PBAT	Incubation	Proteomic screening allowed the identify a new esterase, PpEst, that is involved in PBAT degradation.

Organism	Polymer	Experimental conditions	Outcome
Phaeodactylum tricornutum	PET	Microalgae transformation	Expression and secretion of PETase in the algal system under (mesophilic marine) growth conditions
Chlamydomonas reinhardtii	PET	Microalgae transformation	PET hydrolyzation. TPA, a fully degraded form of PET, was detected.
Ideonella sakaiensis	PET	Gene disruption system	PETase and MHETase are essential enzymes for PET digestion.
		Improvement of the thermostability of leaf-branch compost cutinase	Improved PETase can reach up to 90% of PET degradation.
Pseudomonas putida	PBAT, PET	Modified M9 minimal medium. Electrocompetent cells were prepared by a modified standard protocol	Plastic biodegradation assays with the best PET hydrolase expression constructs are genomically integrated into our monomer metabolism. This resulted in various degrees of plastic depolymerization. The surface display of the PET hydrolase and the secretion were successfully

https://doi.org/10.1016/j.ese.2024.100407

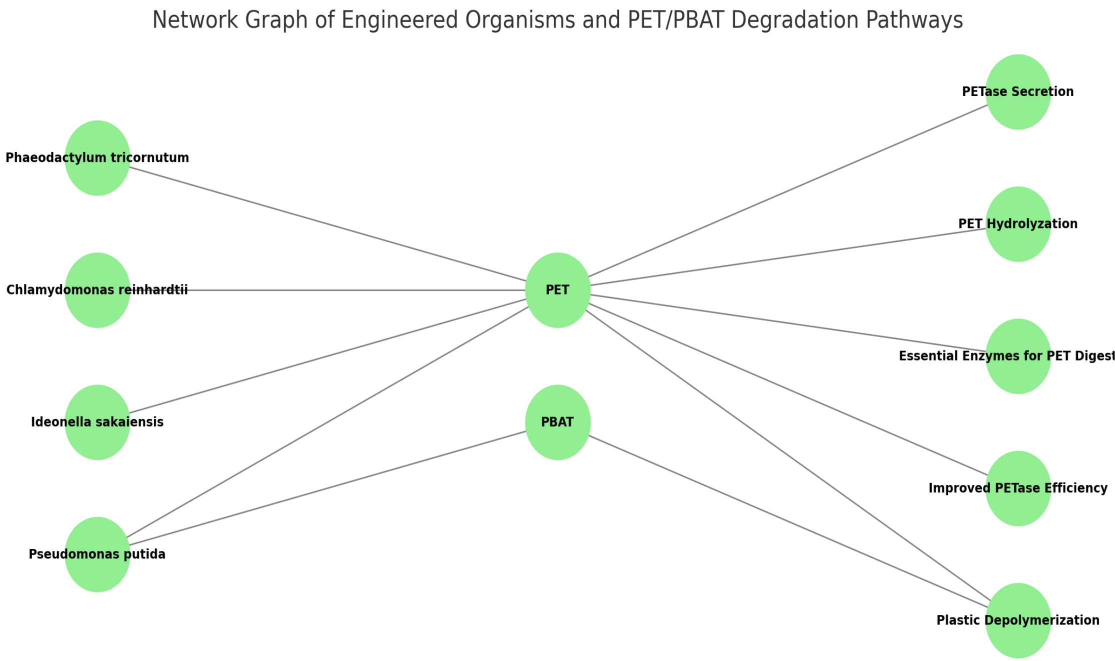
Case Studies



Network graph illustrates the complex interactions between various microorganisms and the polymers they degrade

- The graph showcases a range of organisms, such as *Ideonella sakaiensis*, *Moraxella* sp., and *Klebsiella* sp., each linked to specific polymers like PET and PVC.
- Certain microbes demonstrate specialized degradation pathways. For instance, *Ideonella sakaiensis* is connected to PET degradation leading to significant enzymatic breakdown, a critical pathway for recycling PET-based plastics.
- The connections leading from polymers to outcomes such as methane production indicate potential biotechnological applications in bioenergy.

Case Studies



- Engineered Enzymatic Enhancement: *Phaeodactylum tricornutum* and *Chlamydomonas reinhardtii* showcase the engineering efforts to express and secrete enzymes like PETase, which are crucial for breaking down PET at a molecular level.

  Ideonella sakaiensis has been further engineered to improve the stability and efficiency of enzymes like PETase and MHETase, which are essential for PET digestion. This enhancement is visualized through connections to outcomes like increased PETase efficiency and essential enzyme activity.

  Pseudomonas putida demonstrates a wide range of degradation capabilities, handling both PET and PBAT. The integration of PET hydrolase expression constructs into the genome has led to various degrees of plastic depolymerization, effectively demonstrating the versatility and robustness of engineered bacterial systems.

  The graph links each organism to specific outcomes, such as 'Plastic Depolymerization' and 'Improved PETase Efficiency', highlighting the targeted approaches in genetic engineering to optimize polymer degradation pathways for industrial scale-up.

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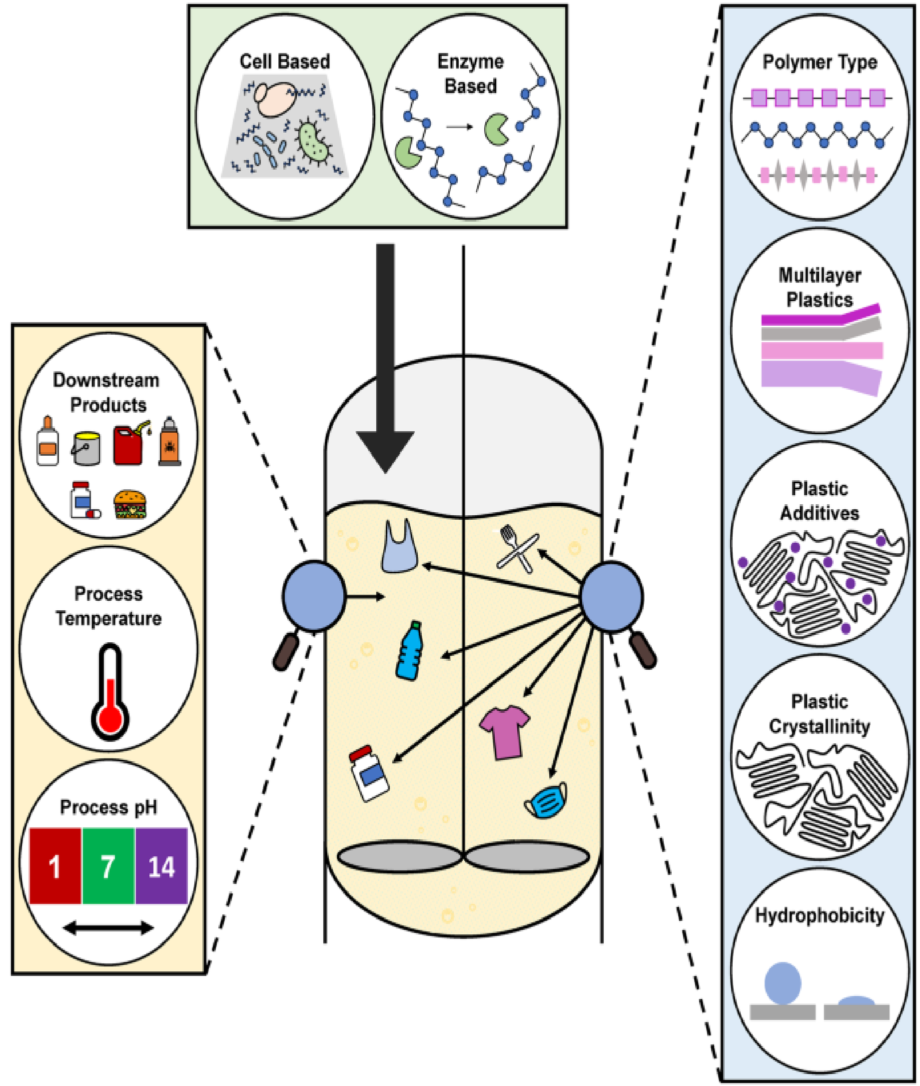
Bottlenecks in Bio-based Remediation

- Coupling technology with economic incentives, financial support, policy support, and waste infrastructure modifications is essential for advancing biobased plastic degradation.
- Current technologies in industrial settings are in early stages and lack the scalability and ease required to compete with mechanically recycled and virgin plastics.
- A comprehensive global effort is necessary to make significant progress in addressing the plastic waste problem.



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https://doi.org/10.1038/s41467-024-49146-8

Thanks