HYDRA Marine Sciences

Environmentally biodegradable plastic polymers: nice to have or a must?

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Webinar Bioplastics
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photo: Andi Eich/HYDRA


We have a problem:
Plastic is found
in the sea
in lakes & streams
in soil
in the air
in plants & animals
in humans

courtesy of NTTI
No-Trash Triangle Initiative

Question:

Is Environmental Biodegradation a solution for the problem of plastic pollution?

courtesy of NTTI No-Trash Triangle Initiative

Question:

Is Environmental Biodegradation a solution for the problem of plastic pollution?

In an ideal world, waste management is the key to success against litter

REALITY

Still a lot

of measures to take

➔ by e.g. redesign,

voluntary and enforced agreements,

EPR schemes,

regulations, laws,

infrastructure, management, etc.

Loss to the environment ➔

https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

How does plastic reach the environment?

4 Categories:

Intentional Input

High Risk of Loss Applications

Abrasion

Littering & Release

Intentional Input

Most direct form of plastic input

Products intentionally designed to remain in the environment

’Made-to-stay products’

Accumulation of plastic in the environment accepted as part of its function, or as consequence of its use

Intentional input

made-to-stay applications, recovery is not foreseen, accumulation accepted

Applied to remain in the environment

High Risk of Loss Applications

High likelihood of being lost partially or in total during use

Often ends up in nature due to carelessness or poor recovery practice

Agriculture:

Plastics are used in high risk-of-loss applications & introduced on purpose or intentionally left behind

In agriculture, plastic saves water, agrochemicals, extends the season, assures food supply...

But

comes with a price:

Plastic also can cause

obvious damages

e.g. to soils,
crop yields,
livelihoods, health …

Fisheries & aquaculture:
High risk-of-loss applications

and many others

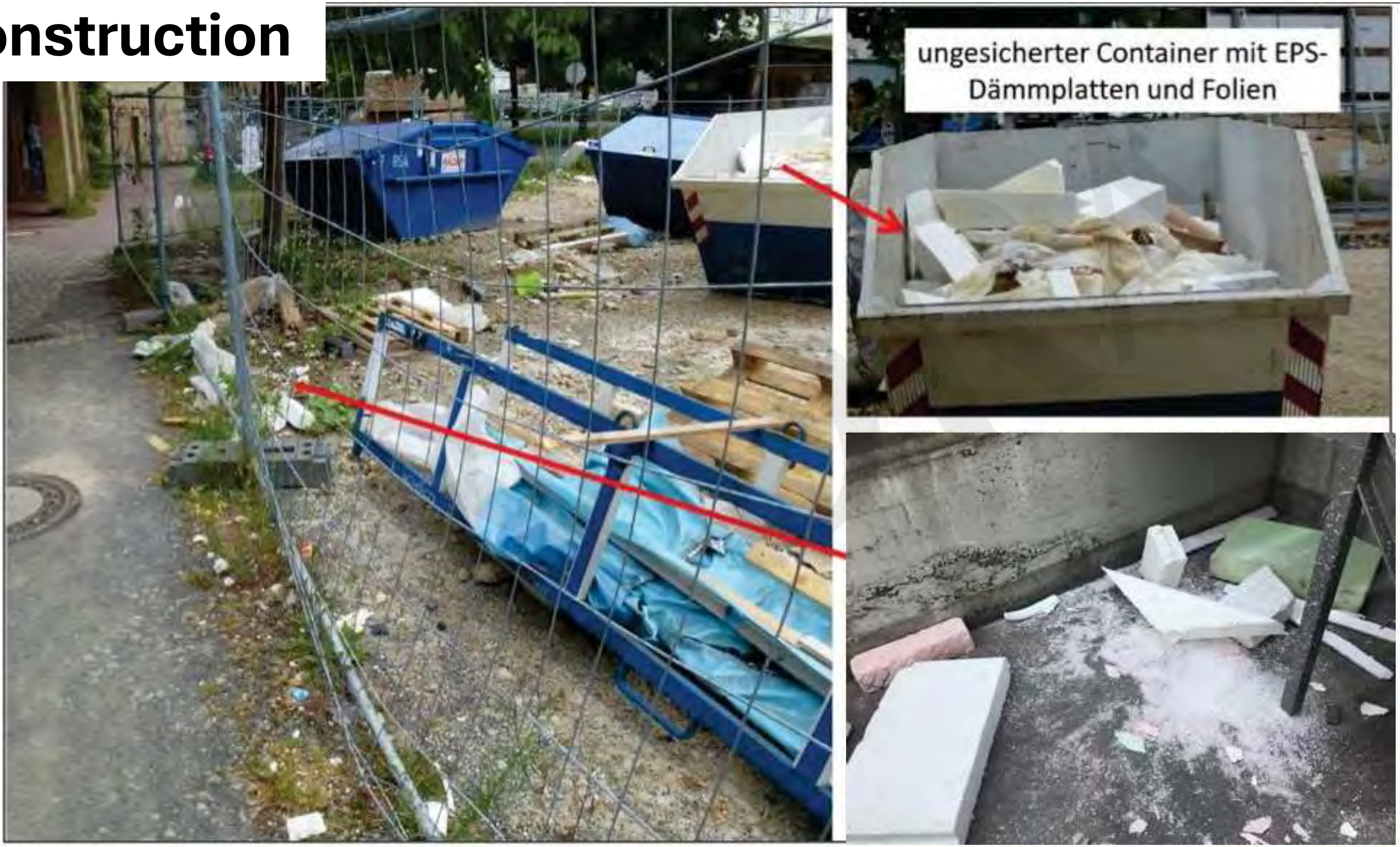
Fisheries & aquaculture

Fish boxes

Fish Attracting Devices

Mussel socks

Construction



Ungesicherter Bauabfallcontainer mit EPS-Dämm-platten und Folien sowie daraus entstandene Verwehungen der Abfälle

Source: Breitbarth 2017

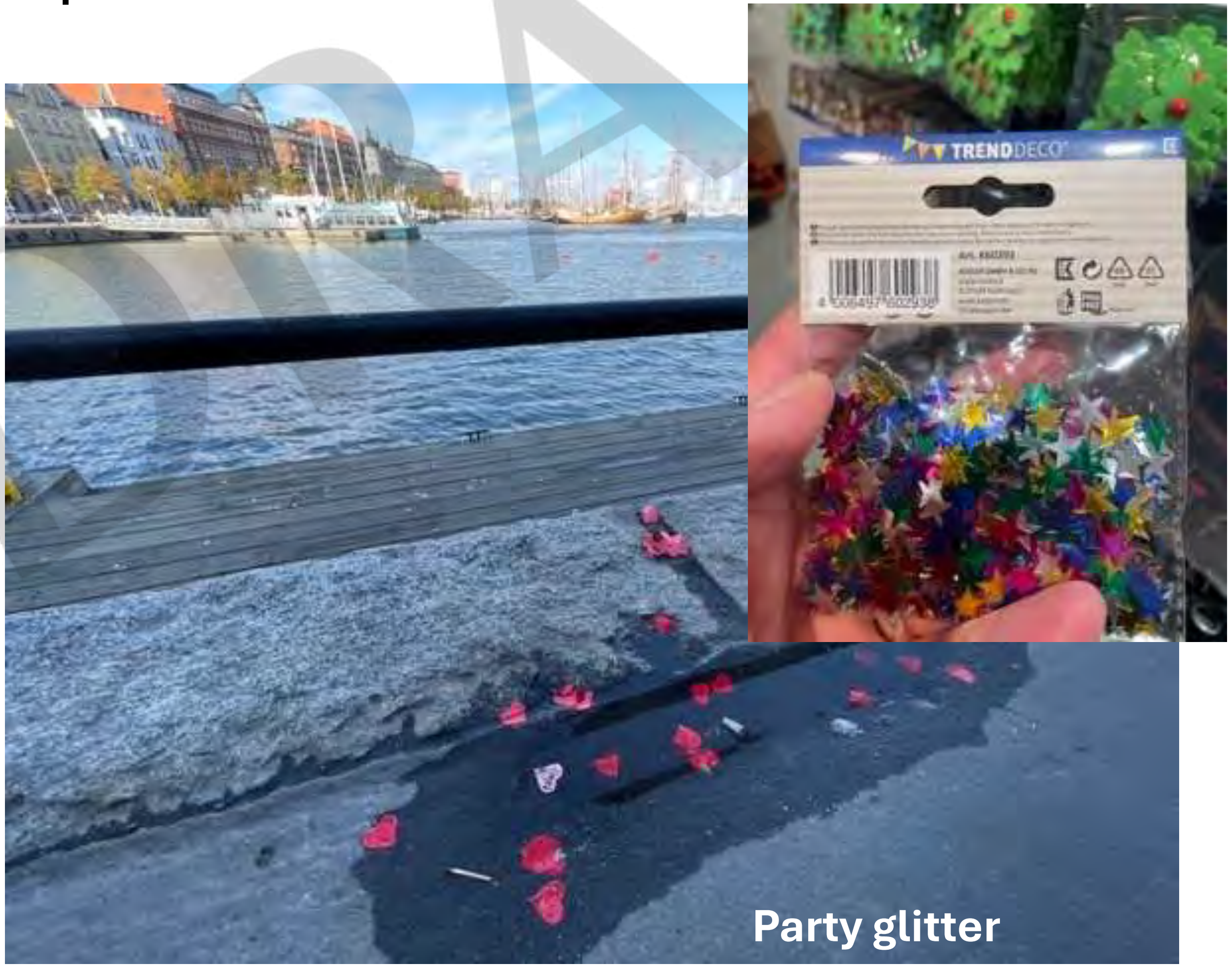
Micro-Plastics generated by cutting, sawing, shaping, drilling of macro-plastic items on open construction sites

intentionally added

Other sectors

with high risk of loss during use & accepted loss to the environment

artificial sports greens



Party glitter

Other applications

with high risk of loss during use & accepted loss to the environment

... and many more

Abrasion

Release of fragments, micro- and nanoplastics due to wear and tear of products during regular use

Sources largely unavoidable, as the particle loss is inherent to the function and aging of the material

Abrasion: Fiber shedding

textiles, wear & tear, accepted loss to the environment

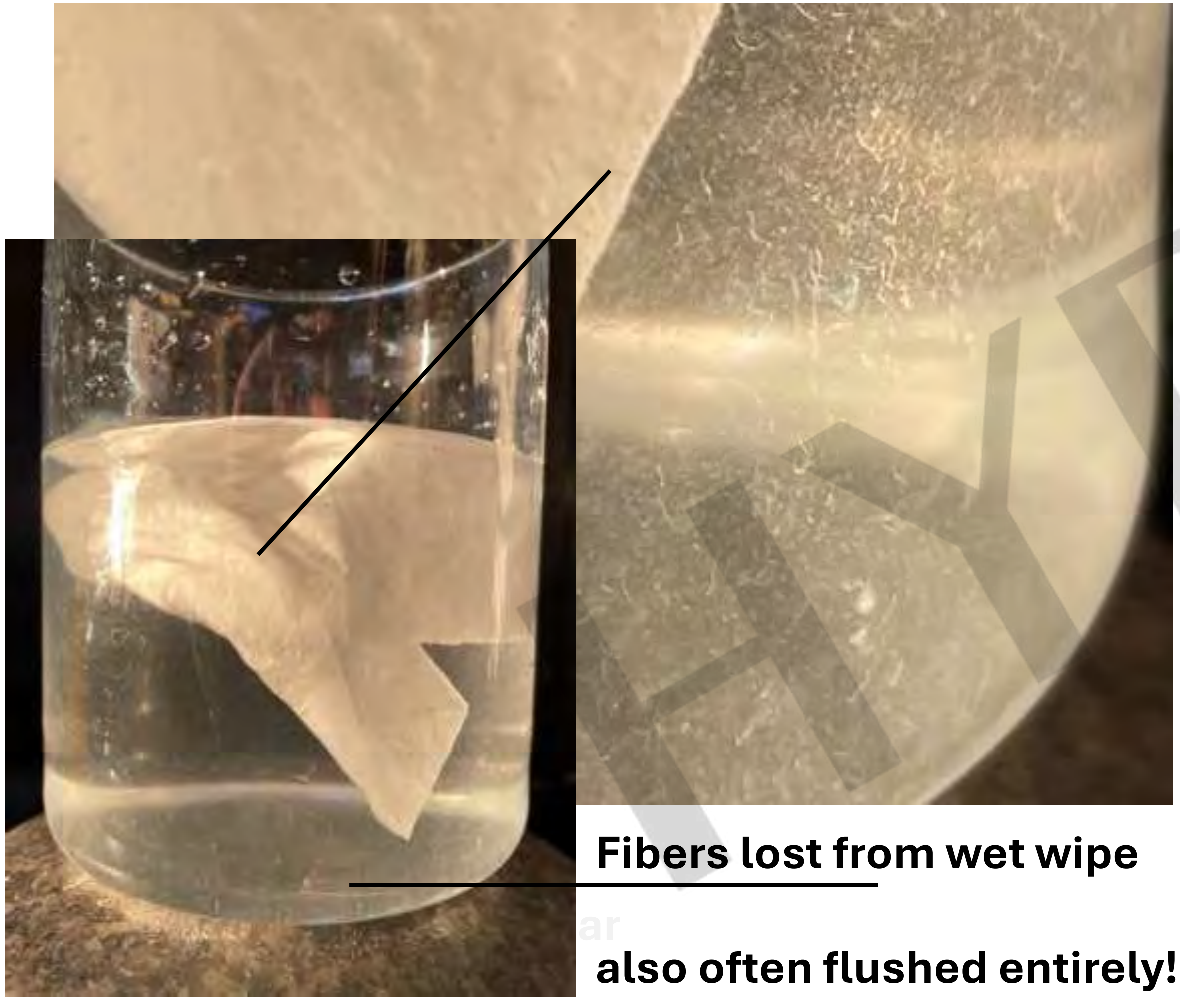

clothing


decoration


Flags, outdoor textiles

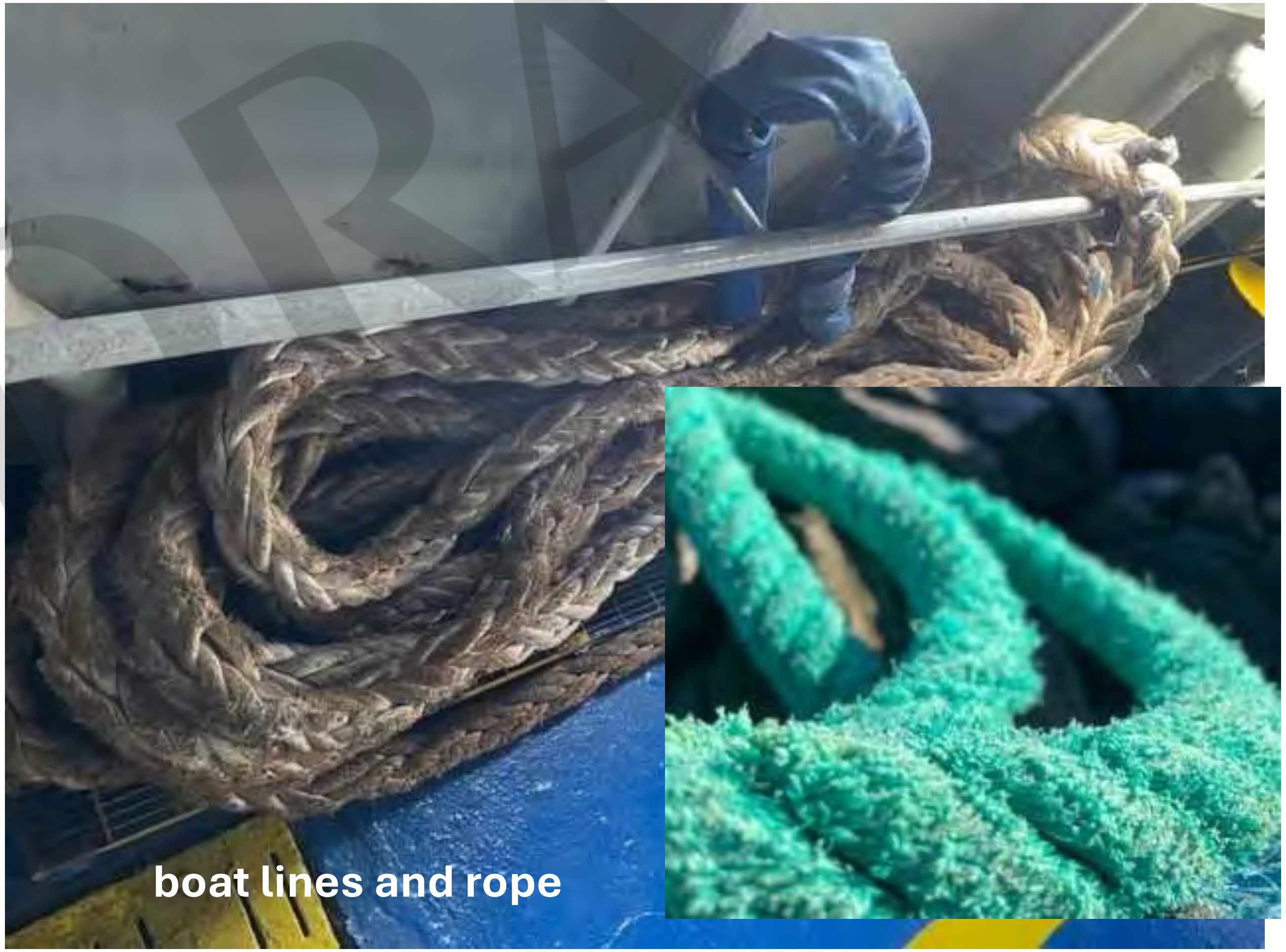
... and many more

Release: Fiber shedding & abrasion



Fibers lost from wet wipe

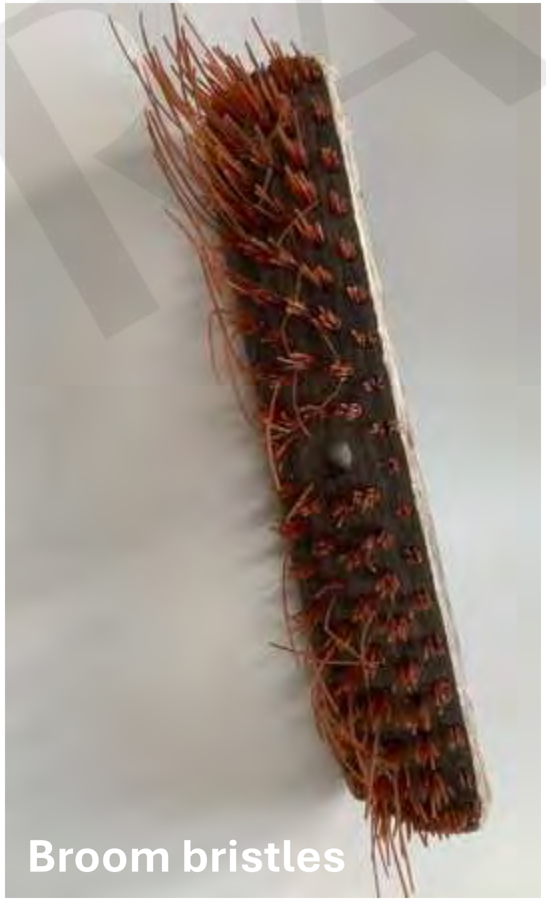
also often flushed entirely!



Other applications

with abrasion, wear & tear, accepted loss to the environment

Tyres



Broom bristles

Lawn trimmer filament

... and many more

Littering & Release

Most discussed source of plastic pollution (primarily packaging waste)

On individual level (in regions with sufficient waste management):

due to negligence and lack of awareness

On system level (in regions with no or poor waste management):

lack of alternatives, literally all waste is released to the environment, or burnt

Littering (intentionally throwing garbage away)

~500 million per year used (GER)

5.4 trillion per year used globally

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Measures:

- awareness (over and over again…)
- waste management

How does plastic reach the environment?

With no waste management in place:

All waste is released into the environment or burnt!

global perspective

Some
2.7 billion
people do not have their waste collected.

Lack of waste management (no other possibility)

Lack of waste management (no other possibility)

The other
'waste management'

courtesy of NTTI
No-Trash Triangle Initiative

Rudimentary waste management

courtesy of

NTTI
No-Trash Triangle Initiative

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Rudimentary waste management

courtesy of

NTTI
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High risk of loss for **systemic reasons**

e.g., hygiene waste

global perspective

Source: Ellen MacArthur Foundation,
https://bbia.org.uk/wp-content/uploads/2020/11/A-Circular-Economy-for-Nappies-final-oct-2020.pdf

What are the Solutions?

To minimize accumulation of persistent (micro-)plastic in the environment we

- must manage (much) better
- could stop using them (will not be accepted in most cases),
- or replace persistent plastic applications with environmentally biodegradable alternatives

If we want to **change the material**, we need to consider:

- Requirements for **functional life** during use

- Requirements for the **end of life** after use

  - Material properties
    (chemical composition, molecular structure, physico-chemical properties)

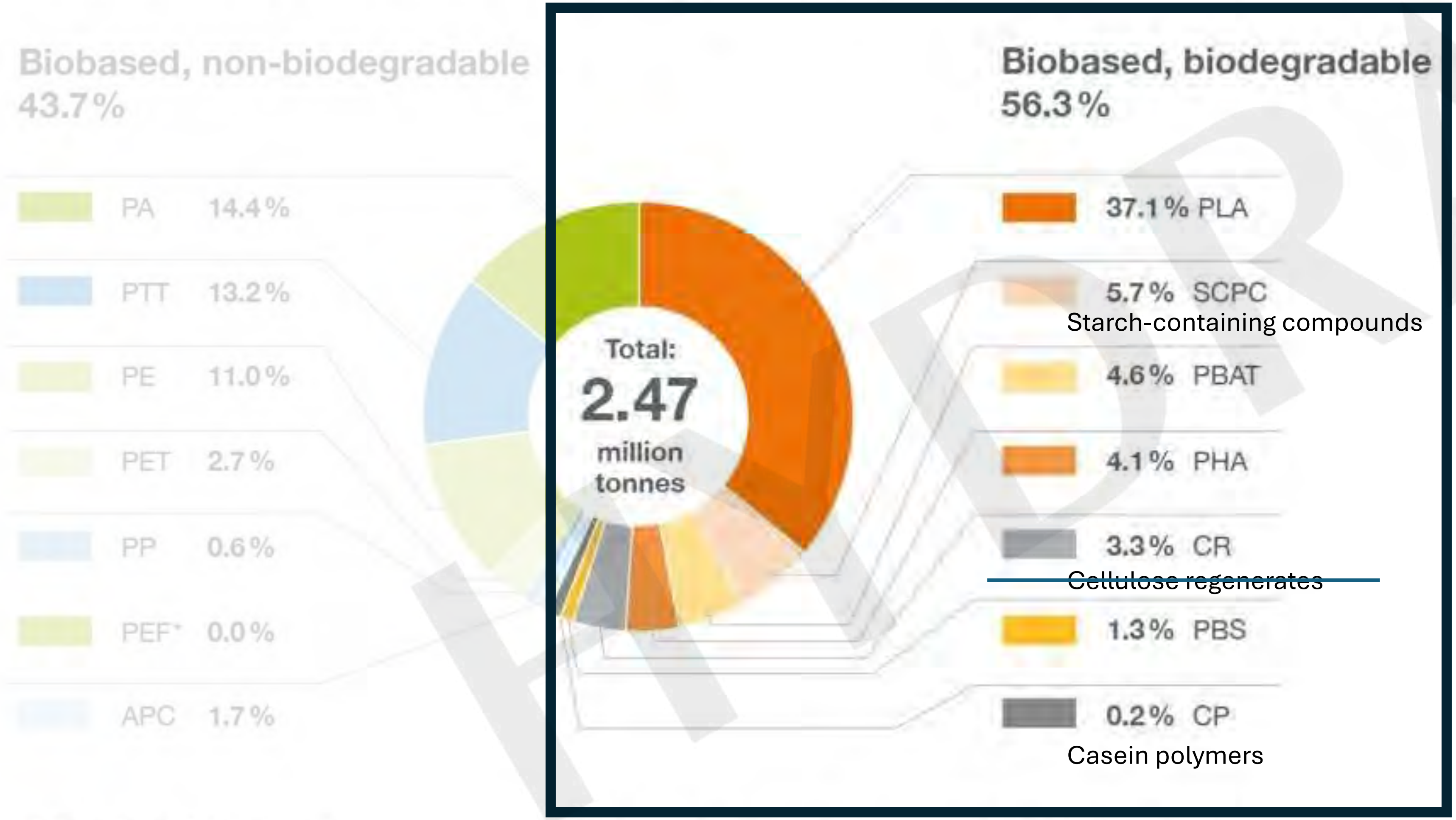
  - Degradation: Mode of **depolymerization and mineralization**
    (chemical and/or enzymatic depolymerization, microbial uptake)

Which materials/polymers do we have?

What can we expect from them, what not?

Which Material Options do we have?

Global production capacities of bioplastics 2024



Basically,
a handfull of polymer families

+ emerging:

P -X- F
2,5-furandicarbolic acid based

(see REBIOLUTION EU Project, H2020 #*101082040*)

APC	Aliphatic Polycarbonates	PBS	Polybutylene Succinate and Copolymers	PHA	Polyhydroxyalkanoates
CP	Casein Polymers			PLA	Polylactic Acid
CR	Cellulose Regenerates	PE	Polyethylene	PP	Polypropylene
PA	Polyamides	PEF	Polyethylene Furanoate	PTT	Polytrimethylene Terephthalate
PBAT	Poly(Butylene Adipate-co-Terephthalate)	PET	Polyethylene Terephthalate	SCPC	Starch Containing Polymer Compounds

* PEF available at commercial scale as of 2024

Source: European Bioplastics, nova-Institute (2024)

HYDRA's role

From screening tests for polymer development
and off-standard tests for research
to standard tests for certification of product performance

Determine biodegradability
(= material-inherent potential to be completely mineralized to CO_2 at all)

Quantify (environmental) biodegradation rates

How to determine biodegradability?

(= material-inherent potential to be completely mineralized to CO_2 by microbes, $C_{residual} = 0$)

$$C_{plastic} = CO_2 + C_{biomass} + \cancel{C_{residual}}$$

No persistent
micro- or nanoplastics
or intermediates

The conditions for *bio*degradation:

***bio* means life, life requires *water* where *microbes* can be *active*.**

No water, no life. No microbes, no biodegradation.

→ Pure rainwater, or dry soil may not work well …

Lab-scale respirometry

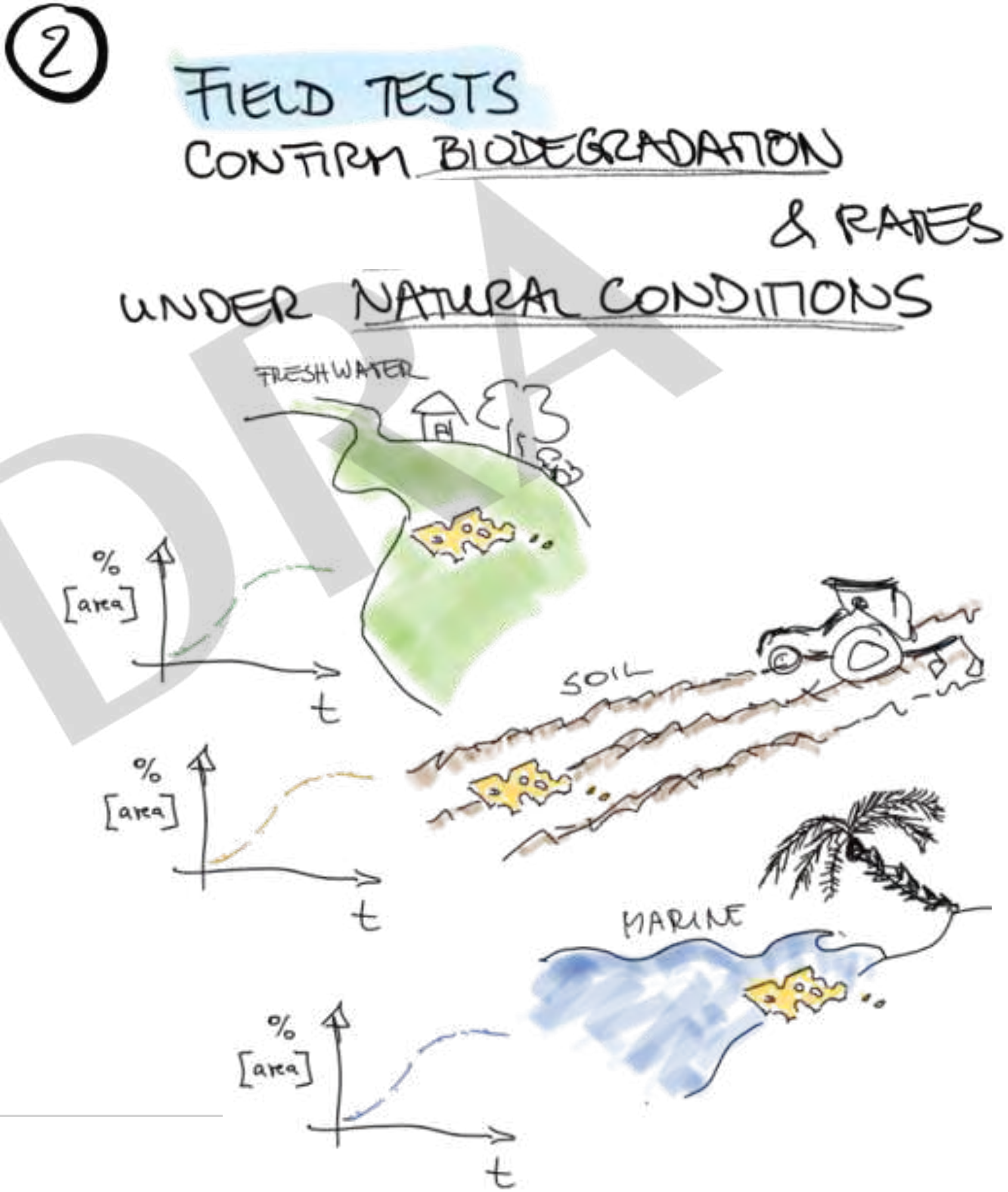
Quantification of mineralization product CO_2 from polymer carbon

Mineralization tests under optimized conditions with water, sediment or soil

"Put the ocean in a small bottle"

in collaboration with ECHO INSTRUMENTS

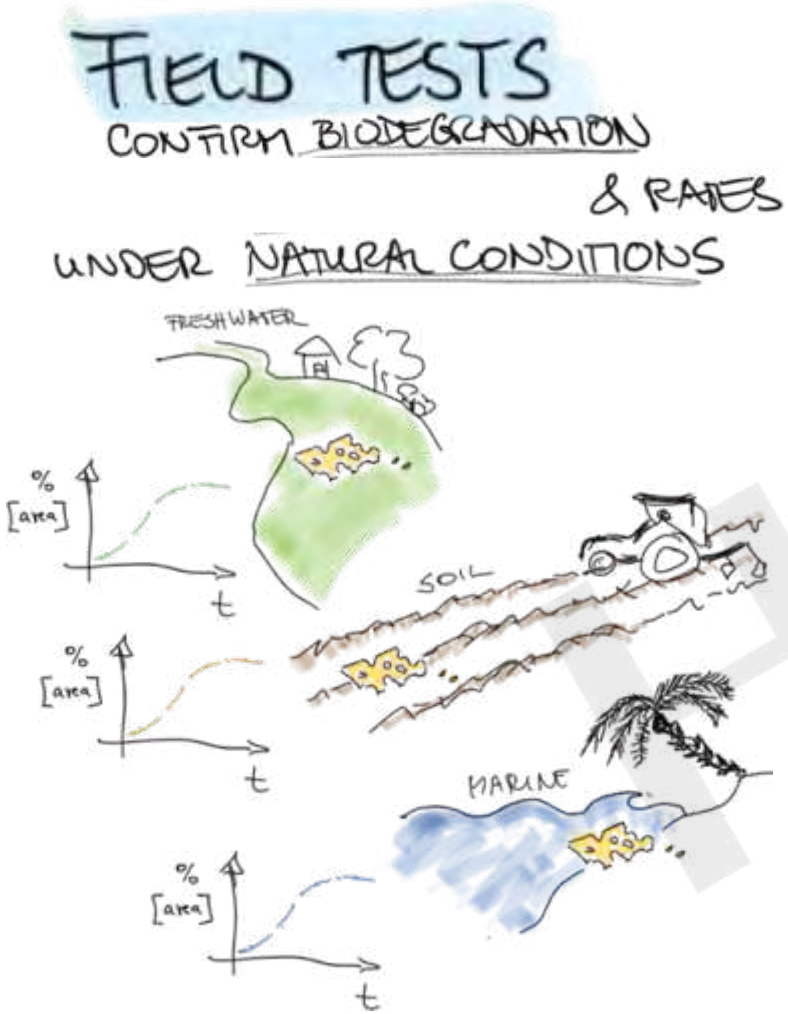
From biodegradability to biodegradation rates

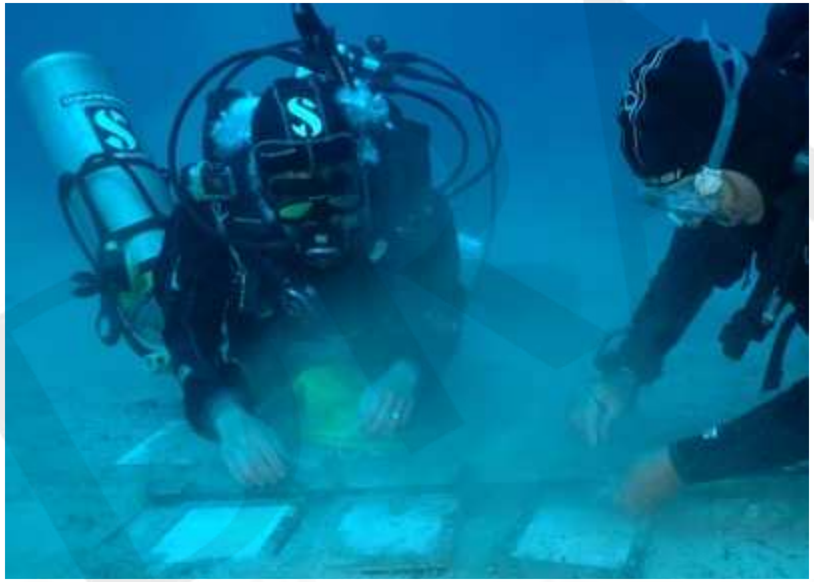


In-situ field tests

Disintegration as proxy for biodegradation

(biodegradability proven before in lab tests)





in collaboration with

partial funding

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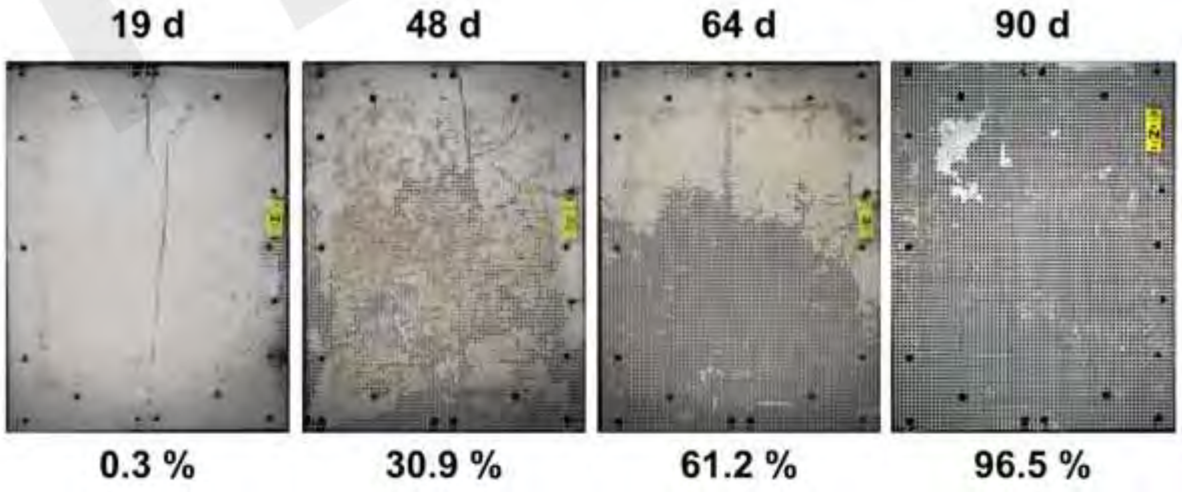
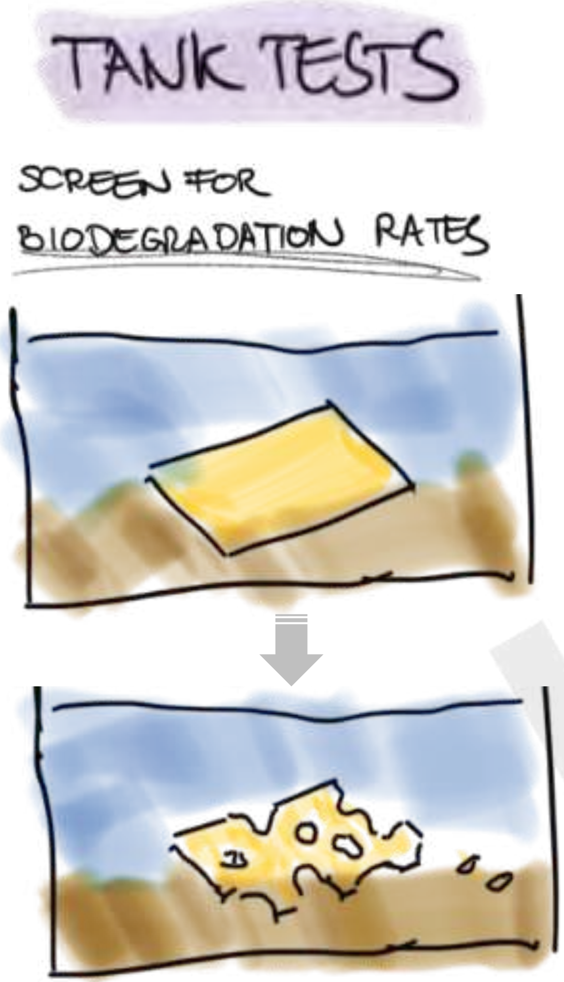


e.g. film as test material

(from: Lott et al., 2020)

Mesocosm or tank tests

Quantification of disintegration as proxy for biodegradation in *manipulative* experiments



e.g., to compare materials or environmental scenarios

Data Modelling (2-D objects)

Quantification of disintegration as proxy for biodegradation

(biodegradability proven before in lab tests)

in collaboration with

BASF We create chemistry

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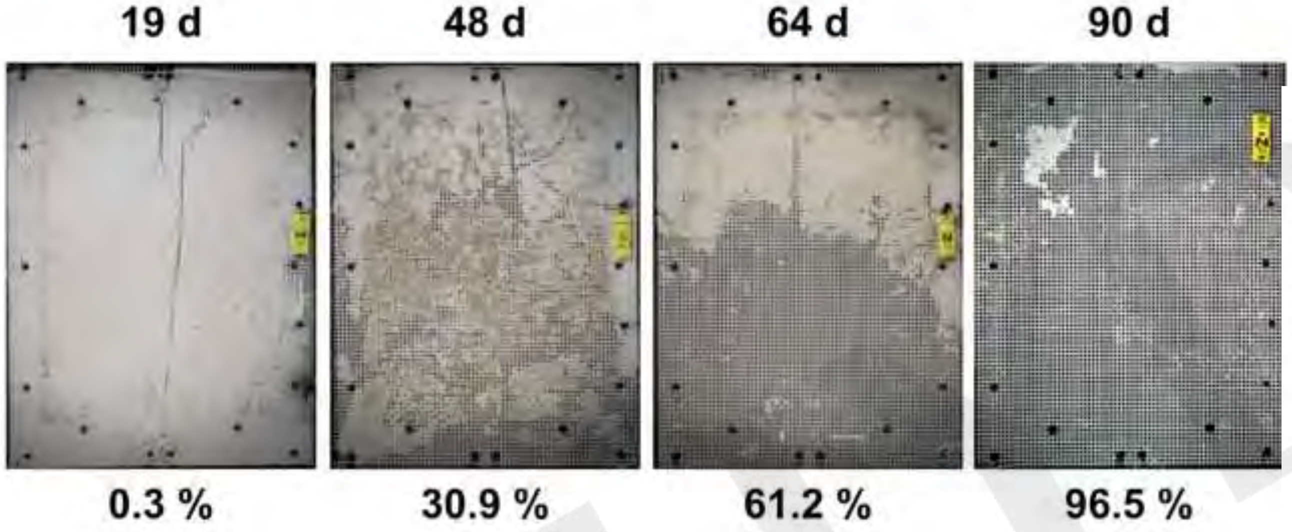
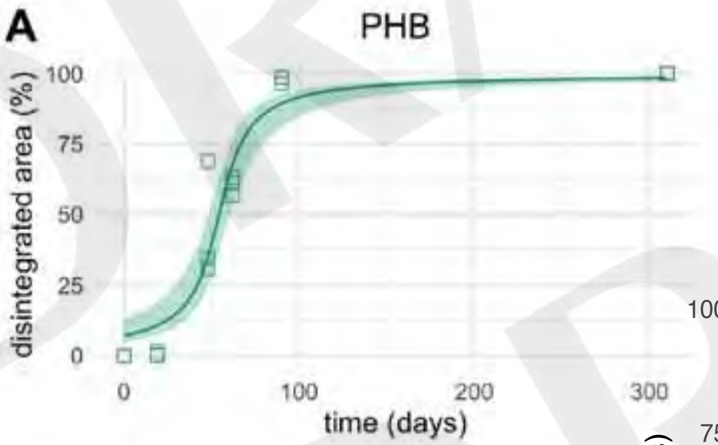
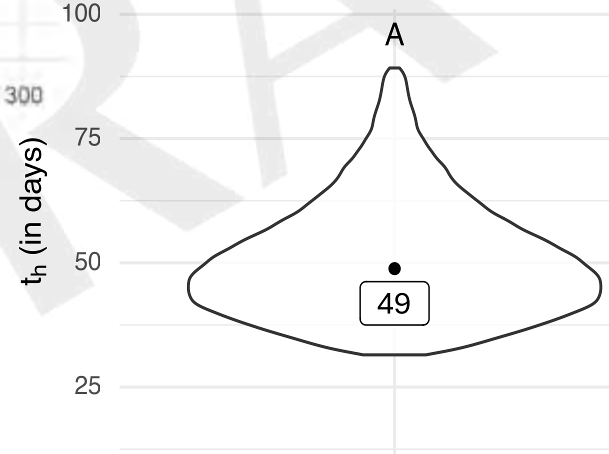


Disintegration time series



Disintegration kinetics



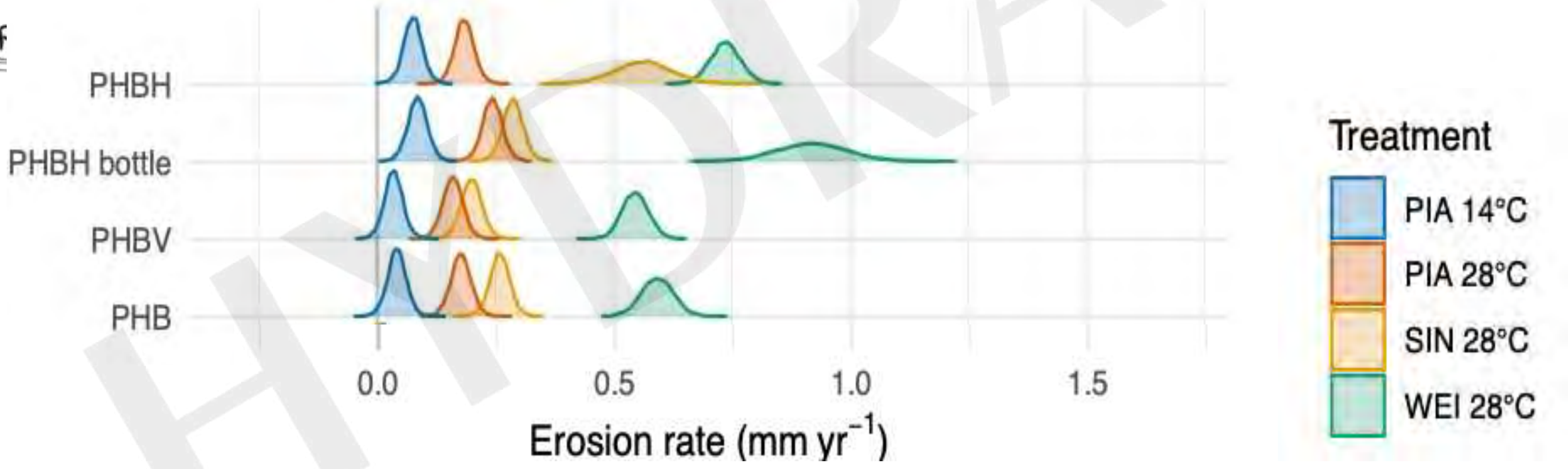
Modeled scenario-specific disintegration half-life

(from: Lott et al., 2020)

Data Modelling (3-D objects)

Quantification of surface erosion as proxy for biodegradation

Surface Erosion Rates **on sediment-water interface**



e.g., to compare materials or environmental scenarios,
here: freshwater & marine sediments

in collaboration with

Nestlé Research

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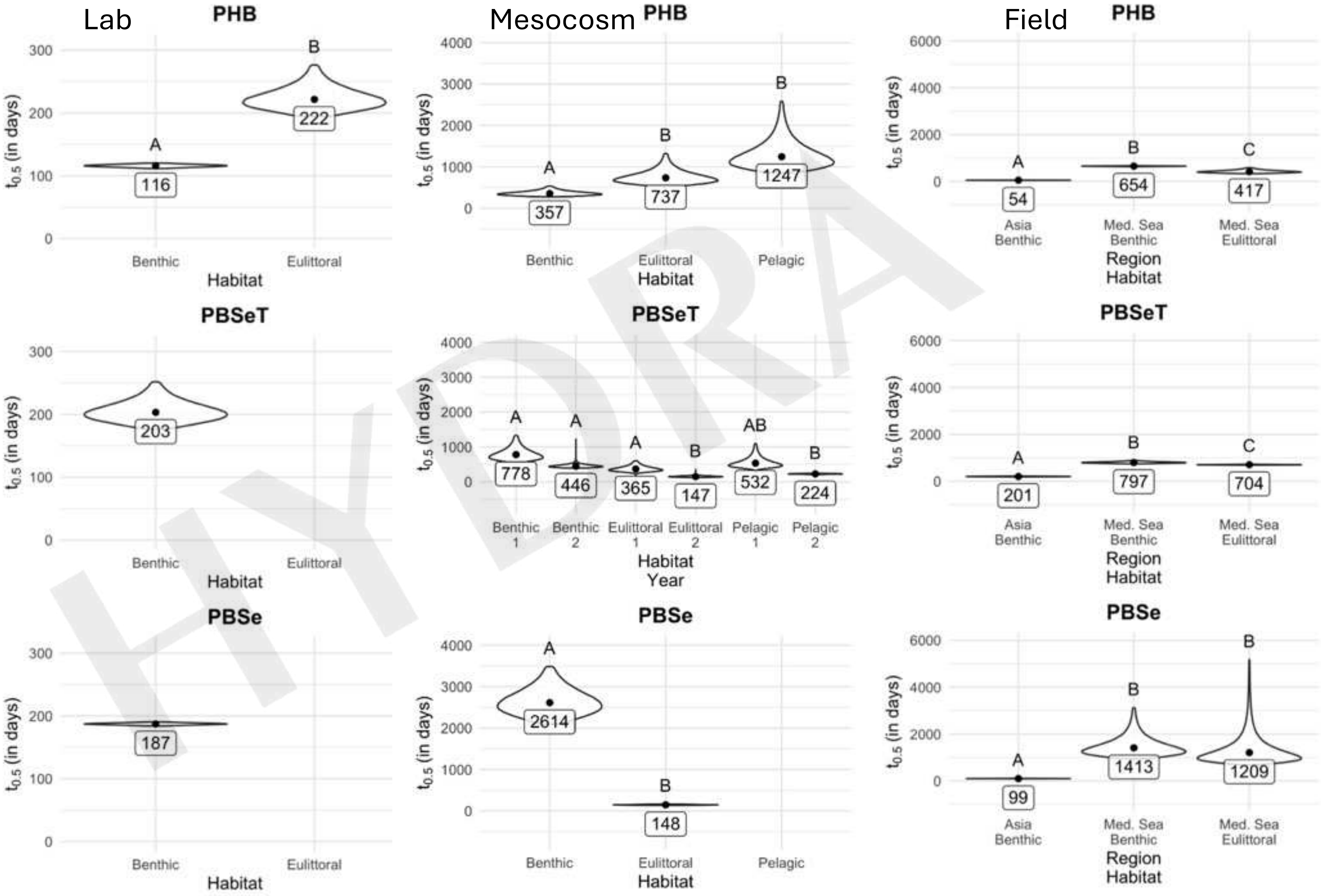
Specific Half-lives for comparison

Meanwhile ~1000 half-lives modeled for specific scenarios



Lott *et al. (2021)*,
Front. Mar. Sci. 8:662074

Data from 3-tier approach combined:

Proof of environmental biodegradability

Laboratory test

ISO 19679

Biodegradation rates in reality

Field test

ISO 22766

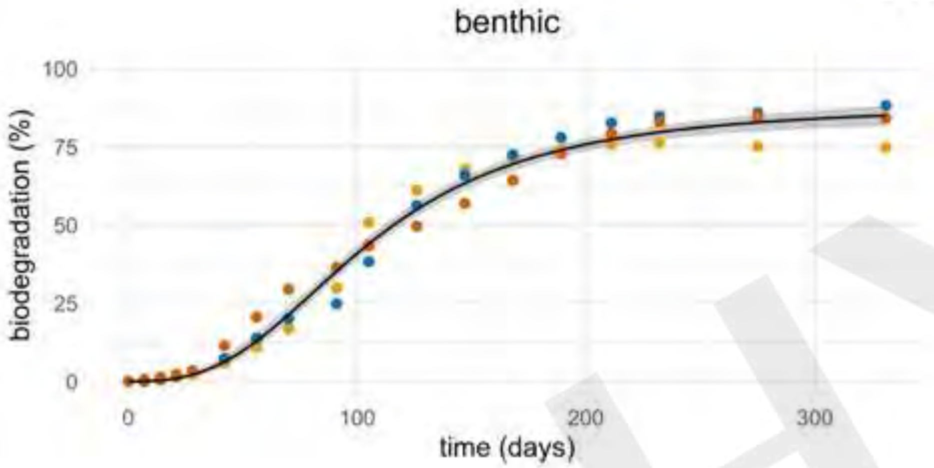
14-25°C (Med); 28°C (Asia), day/night, flow, low nutrients

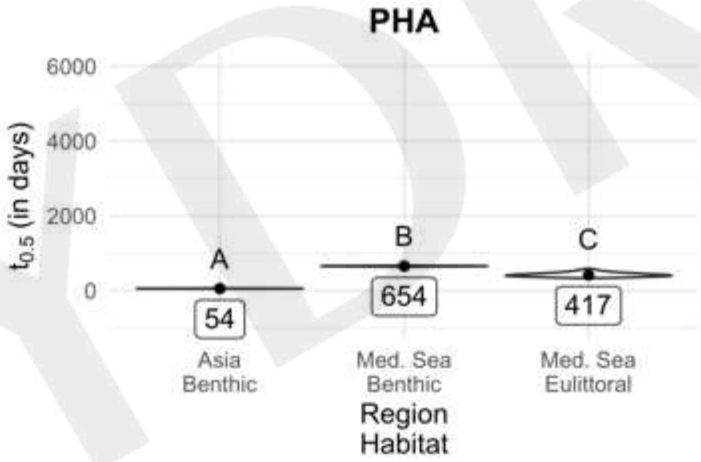
Biodegradation rates in relevant conditions

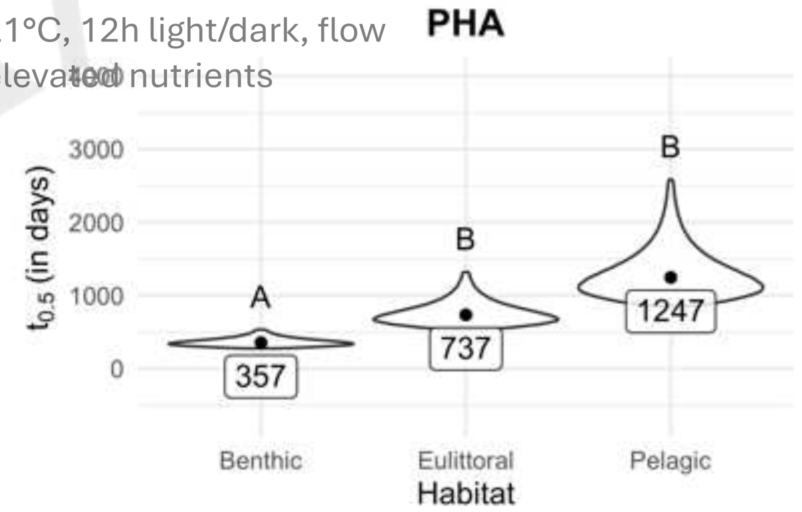
Tank test

ISO 23832, adapted after ASTM D7473

21°C, 12h light/dark, flow elevated nutrients







Example PHB film, 85 *μm* thick

Data for Evaluation, Life Cycle Assessment & Certification

e.g.

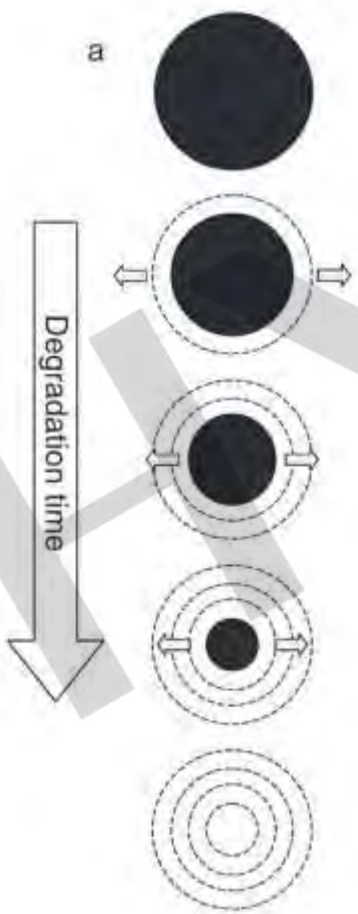
Different degradation behaviors:
Surface erosion vs. bulk degradation of biodegradable polyesters

Surface erosion

typical for e.g. PHAs, PBS, PBAT etc.

Enzymes cannot penetrate the bulk polymer

Surface erosion

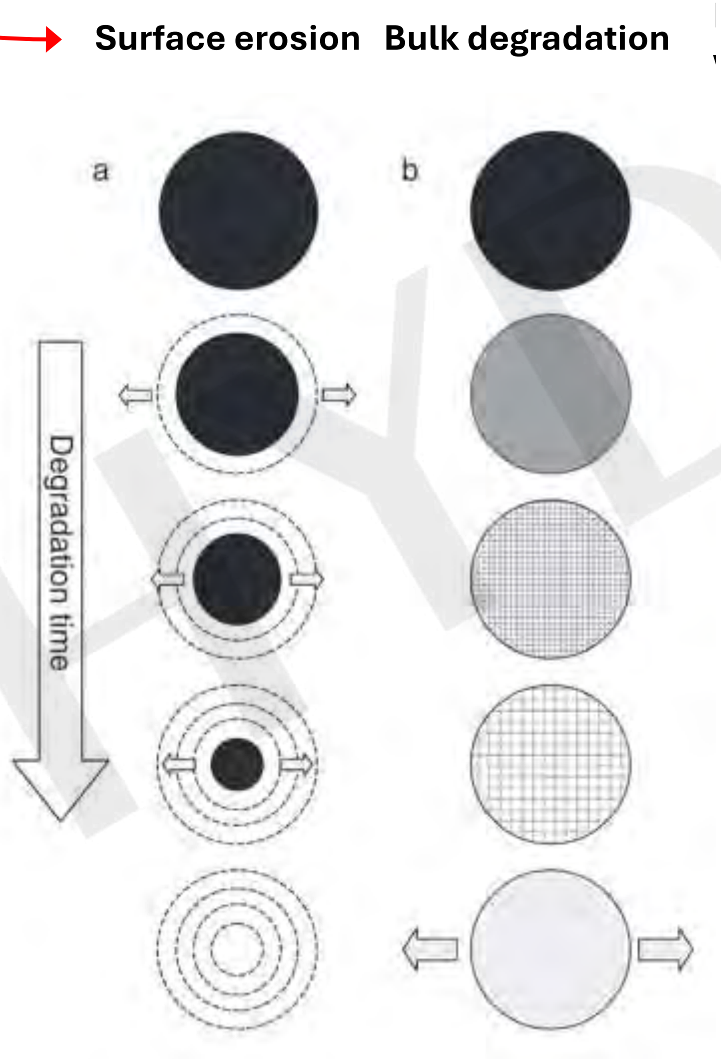


Surface erosion vs. bulk degradation of different biodegradable polyesters

Surface erosion
typical for e.g. PHAs, PBS, PBAT etc.

Bulk degradation process typical for PLA

Enzymes cannot penetrate the bulk polymer



but water may diffuse into some polymers

graphic from Farrar (2008)

Example: Meta-Study on PLA (2023-2024) by HYDRA

A meta-study on the persistence and toxicity of PLA,
and the formation of microplastics in various environments

HOLLAND BIOPLASTICS

TotalEnergies Corbion NatureWorks futerro

Persistence
of an object is its **ability to remain present in the environment** over an extended period of time, i.e. a **measure of how resistant it is to degradation.**

The term "persistence" can be considered both categorical and relative, depending on the context in which it is used.

Guiding questions: What is the ***persistence*** of PLA in the environment?

What does it imply in terms of

- degradation **processes**,
- degradation **products**,
- the formation of **micro- and nanoplastic**,
- its **lifetime** in the environment,
- and its **potential impact** on organisms and the ecosystem?

Environmental biodegradability is a **system property**

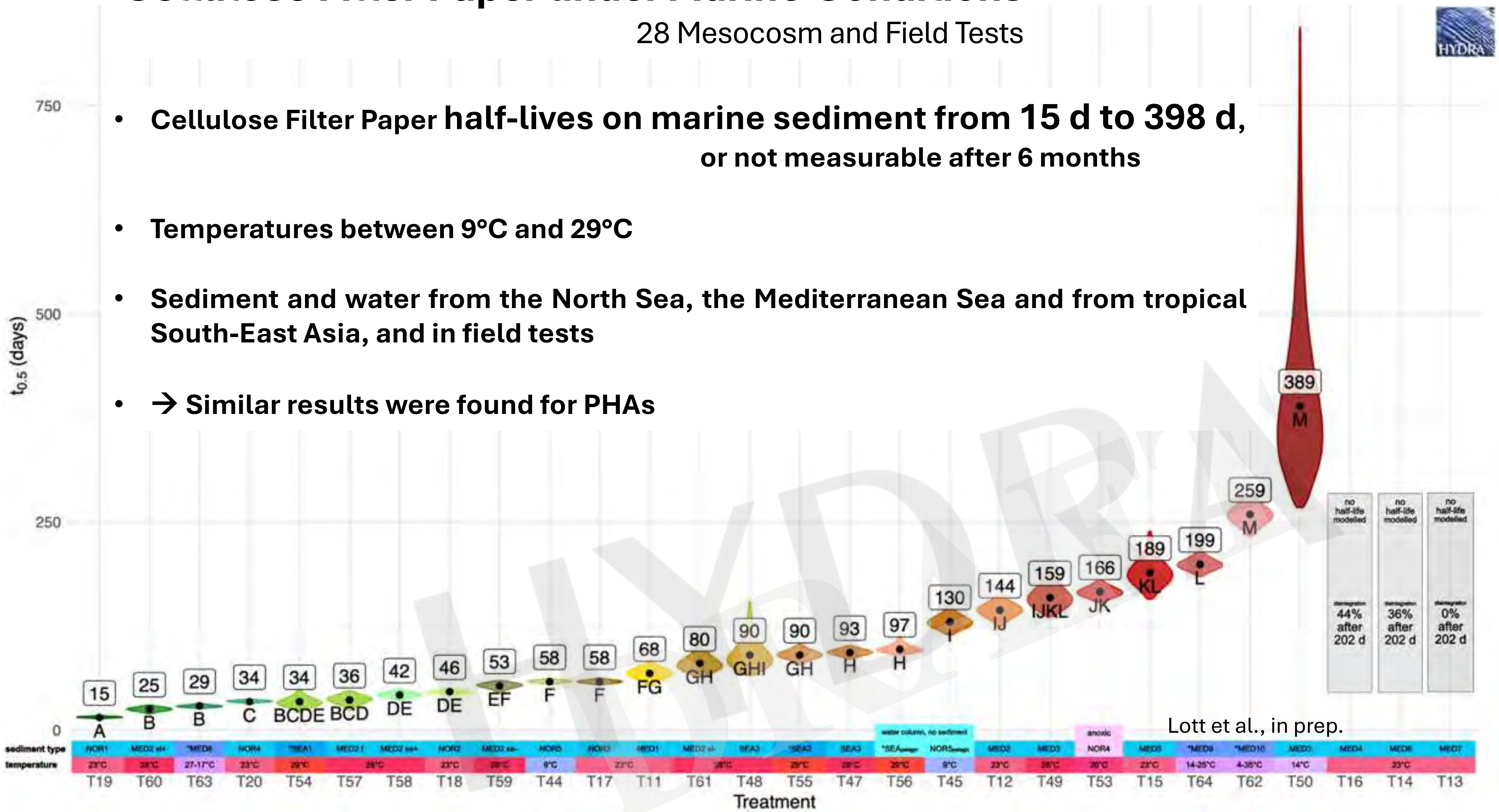
It depends where it ends up

Biodegradation rates of ***biodegradable polymers*** influenced by different environmental conditions

Cellulose Filter Paper under *Marine* Conditions

28 Mesocosm and Field Tests

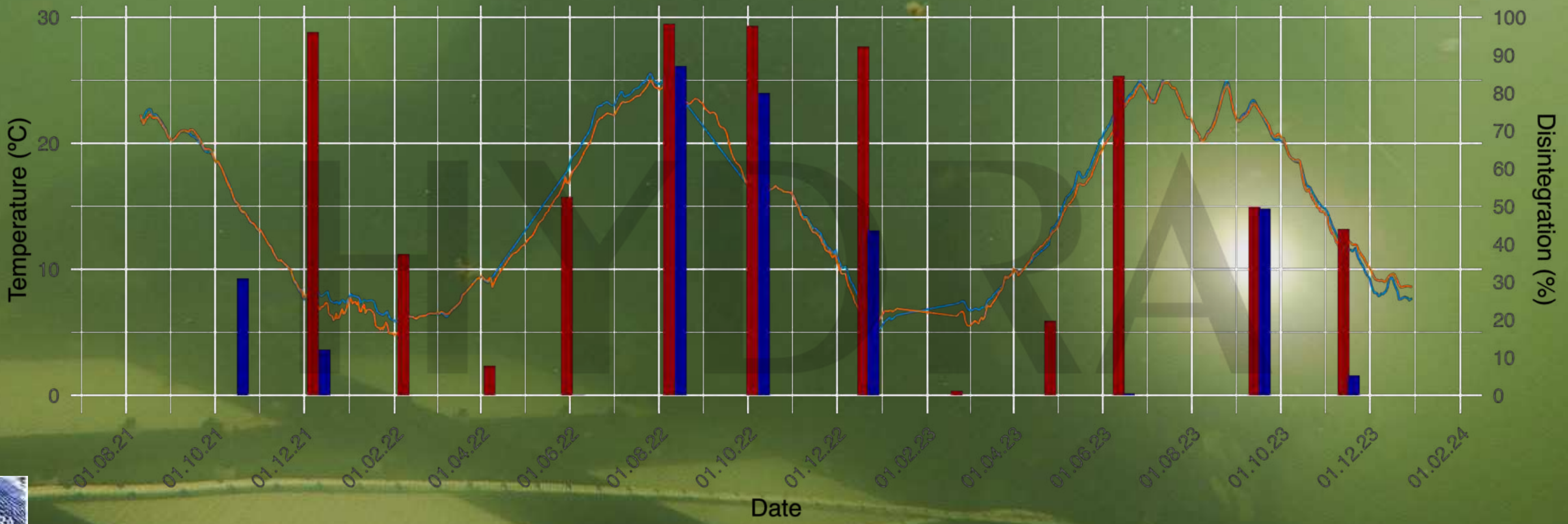
- **Cellulose Filter Paper half-lives on marine sediment from 15 d to 398 d, or not measurable after 6 months**
- **Temperatures between 9°C and 29°C**
- **Sediment and water from the North Sea, the Mediterranean Sea and from tropical South-East Asia, and in field tests**
- **→ Similar results were found for PHAs**



Lott et al., in prep.

Seasonality in temperate climate zones

Temperature effect in a lake



Oxygen availability is variable

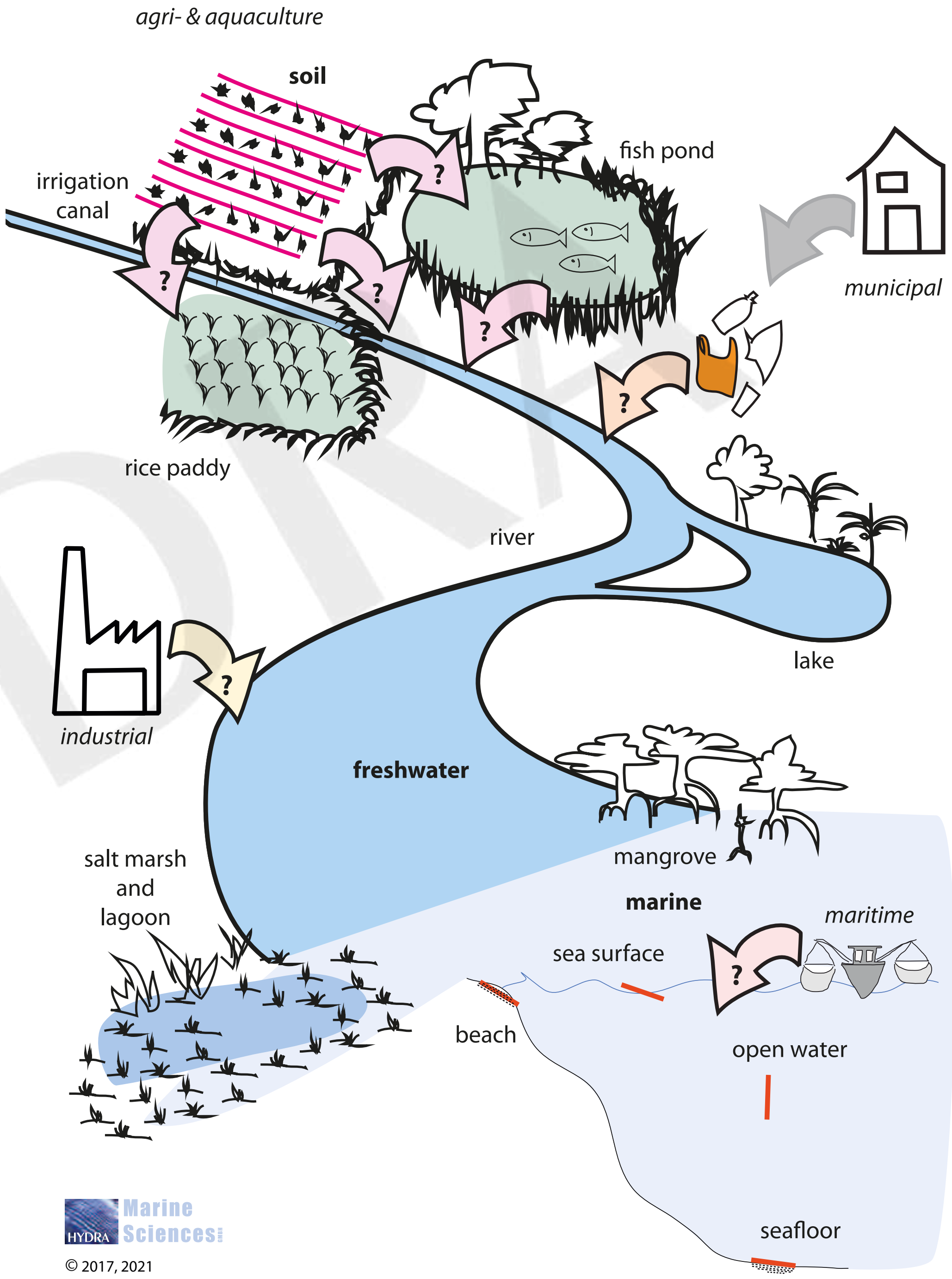
e.g., anoxic conditions in mangrove sediments

PHB
Erosion rate
water
374 µm year^{-1}

PHB
Erosion rate
sediment
659 µm year^{-1}

Where to test?

Challenge: to select the *relevant* conditions & tests



CONCLUSIONS I

Available biodegradable polymer classes fulfil most application requirements, and more polymers are under development.

Available test methods are sufficient for most cases.

Polymers with proven biodegradability in lab tests with environmental inocula also biodegrade in the open environment.

Their specific biodegradation rates may differ by orders of magnitude.

For a homogenous material, once the biodegradation has started there is no reason to assume it would stop unless conditions change.

CONCLUSIONS II

Temperature is a main driver of (environmental) biodegradation, and water is critical, especially in soil.

Variations occur due to local and geographical differences.

Modelled specific half-lives and specific surface erosion rates provide the tool to compare scenarios, materials and products, e.g. for screening.

CONCLUSIONS III

For applications

- with high risk of loss during use,
- where loss is accepted,
- or which are used in the environment to stay,

biodegradation is the only way to reduce the accumulation of persistent plastic in the environment.

For many regions and markets, especially with no waste collection, biodegradable materials should be considered a transitory tool to avoid further plastic accumulation in the environment, in concert with other measures.

Materials are available and their specific biodegradation rates can be measured and tailored to their functional needs and probable environmental fate.

Expectation management:

Environmental scientists, regulation bodies, NGOs, and also material developers, producers, and manufacturers need a basic mechanistic understanding of biodegradation and its limiting factors for informed decision making.

Expectation management:

Environmental scientists, regulation bodies, NGOs, and also material developers, producers, and manufacturers need a basic mechanistic understanding of biodegradation and its limiting factors for informed decision making.

Safe and Sustainable Design strategies needed to create better plastics

With this in mind, biodegradable polymers in many cases are the only solution to prevent persistent plastic pollution in the environment, and in other cases should be considered as interim and/or assisting solutions in a concert of all measures possible along the waste hierarchy:

reduce-reuse-redesign-recycle-remineralize

Innovation Case Studies

New Project: Reduction of the plastic footprint in agriculture

AgriRePlas

Réduction de l'empreinte plastique dans l'agriculture

Un projet transfrontalier pour l'Alsace, le Pays de Bade, le Palatinat du Sud et le nord de la Suisse

Interreg
Cofinancé par l'Union Européenne
Kofinanziert von der Europäischen Union
Rhin Supérieur | Oberrhein

Announcement:

Call for participation: Partners with innovative polymers, formulations, applications, products, please get in touch!

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Upper Rhine Region S-Palatinate, Baden, Alsace, N-Switzerland)

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SCEA Loberger, Eric Mercier, Porte du Ried

BGE, Bio en Grand Est, Colmar

Badischer Landwirtschaftlicher Hauptverband, Freiburg

PLFP, Planete légumes, fleurs et plantes, Sainte-Croix-en-Plaine

FiBL, Frick

EMPA, St. Gallen

partenaires:

AgriRePlas

HYDRA Marine Sciences

Which questions do *you* have?

Material Research & Customized Testing

Standard Tests for Soil, Marine & Freshwater

Visualization & Communication

Concepts & Consulting

contact:

Christian Lott

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recognized test lab PL340

partners

ETH zürich

IKK

MATE

public funding

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REBIOTION