Microplastics in the Environment

Baoshan Xing

Stockbridge School of Agriculture

2023 SNEC WINTER CONFERENCE

March 30, 2023

Presentation Overview

I. Introduction

II. Occurrence of microplastics in the environment

III. Environmental behavior of microplastics

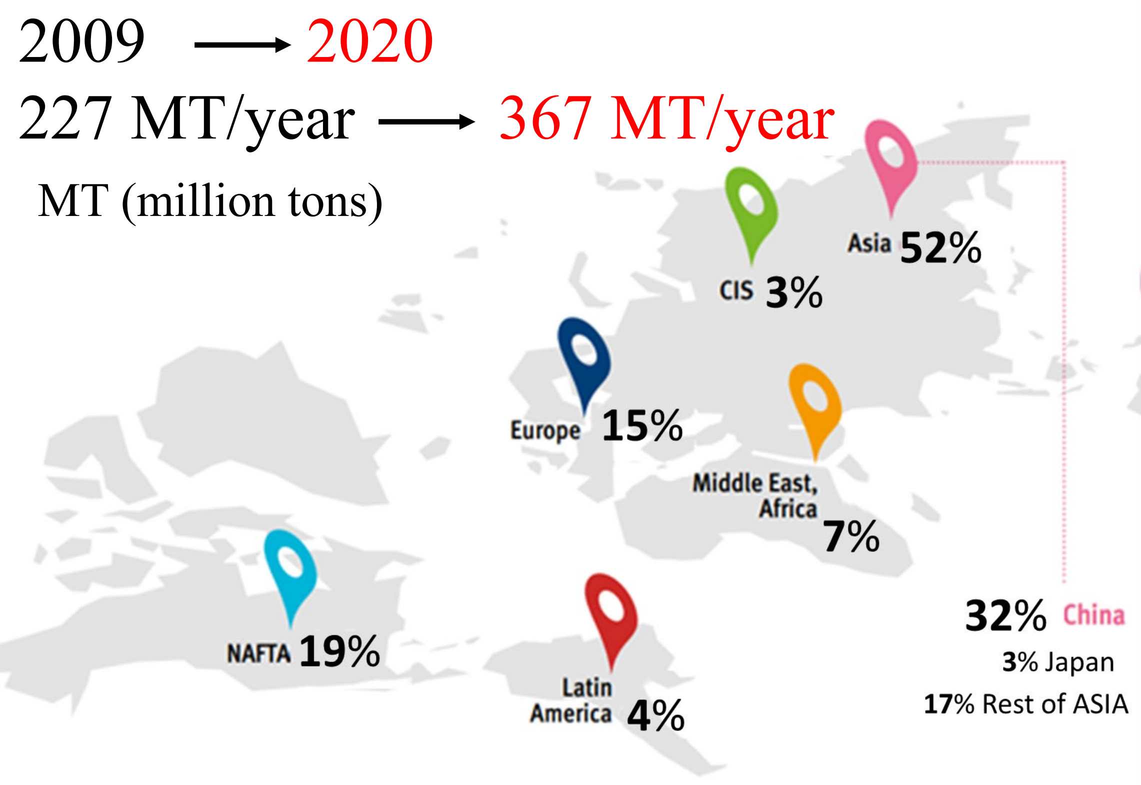
IV. Toxicity of microplastics

V. Exposure and risk of microplastics to human health

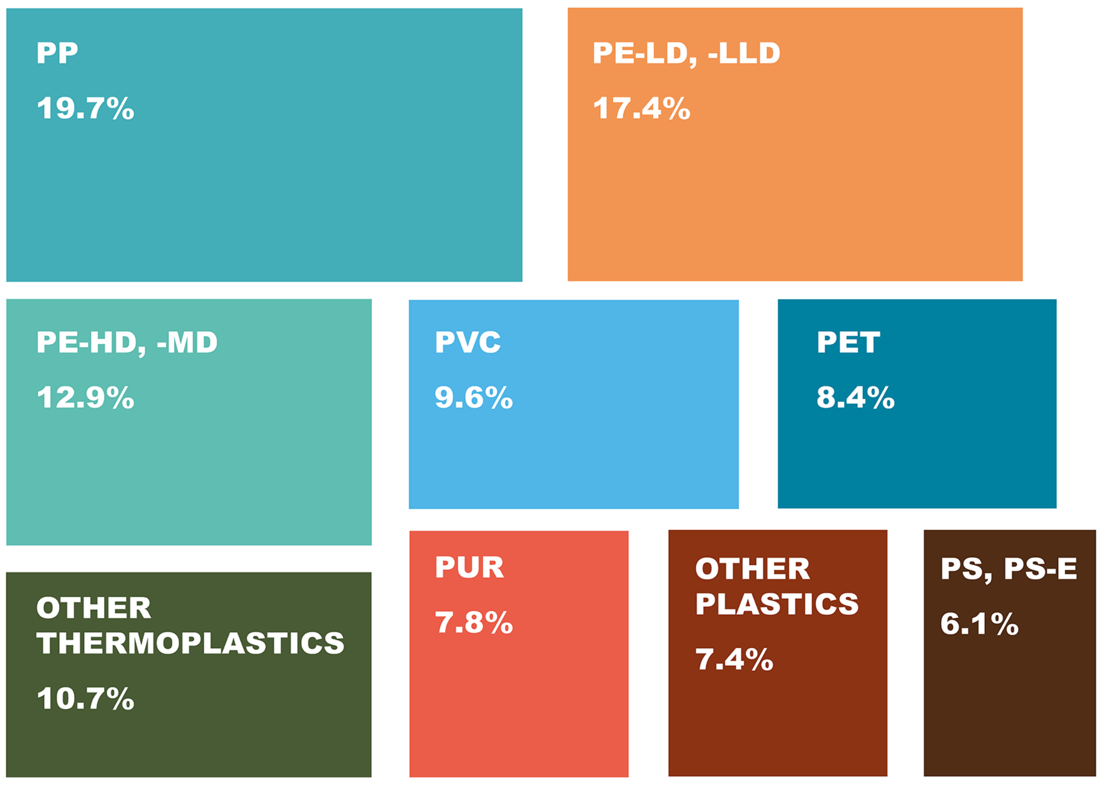
I. Introduction

Global plastics production

Distribution of global plastics production



Plastics demand distribution by type



Plastic Europe, 2021

- Plastics annual production increases rapidly, and China has the highest production
- The biggest plastics demand type is polyethylene (PE) in Europe

Plastics pollution: one of the world's greatest environmental problems

Total plastics waste

Editors, Nat. Commun., 2018; Wang et al., Sci. Adv., 2018

8.37 billion tons of accumulated plastic waste in the world (1950-2019)

Release into ocean

Silva et al., Chem. Eng. J., 2021; Cressey, Nature, 2016

4-12 million tons/year in ocean

Pose threat to marine animals

OceansAsia, 2020

Killing 100,000/year marine mammals and turtles

- Huge amounts of plastics waste enter oceans and pose serious threats to marine ecosystems
- On March 2, 2022, a resolution was endorsed at the UN Environment Assembly (UNEA-5) to end plastic pollution and forge an international legally binding agreement by 2024

The impact of COVID-19 on marine plastics pollution

Masks on the beach

OceansAsia, 2020

Masks could be released into oceans

OceansAsia, 2020

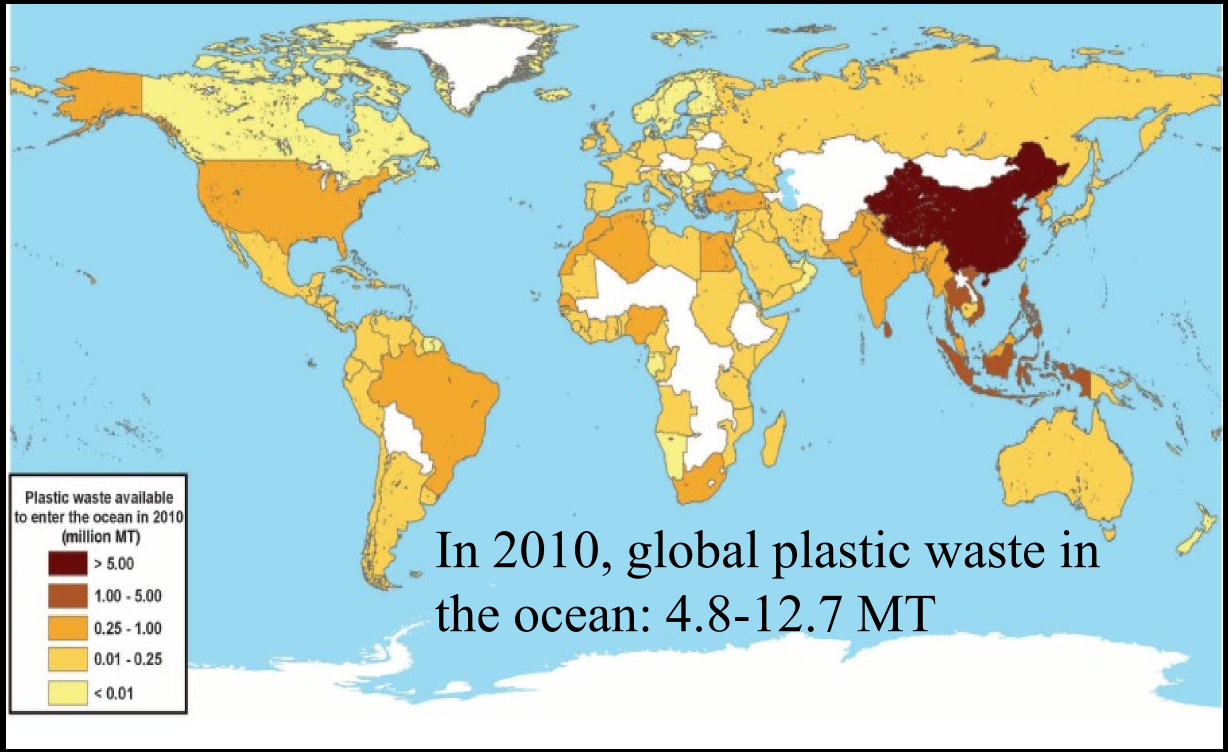
Pose risk to marine animals

Fadare et al., Sci. Total Environ., 2020

- As a result of the COVID-19 pandemic, the number of masks (1.56 billion in 2020) entering the ocean is staggering; about 400-500 years are needed to degrade these masks in the environment
- Disposable masks pose serious threat to marine organisms

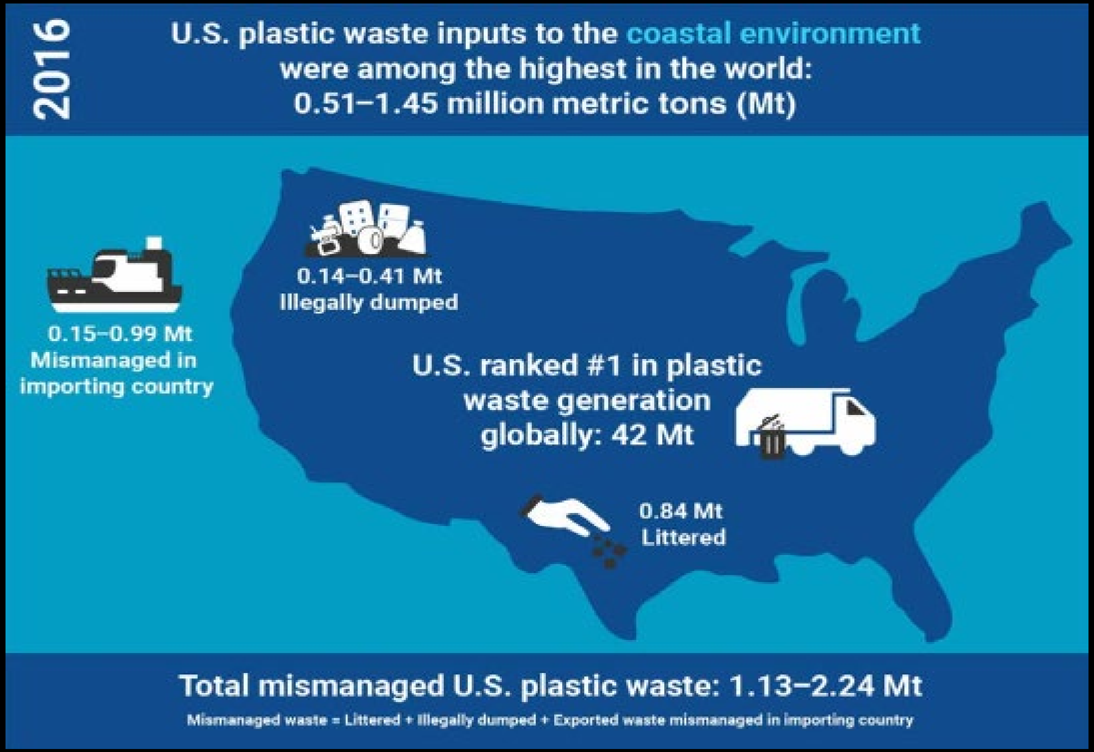
Plastics pollution is a global issue

Plastic waste inputs from land into the ocean



Jambeck et al., Science, 2015

Contribution of plastic waste by U.S.

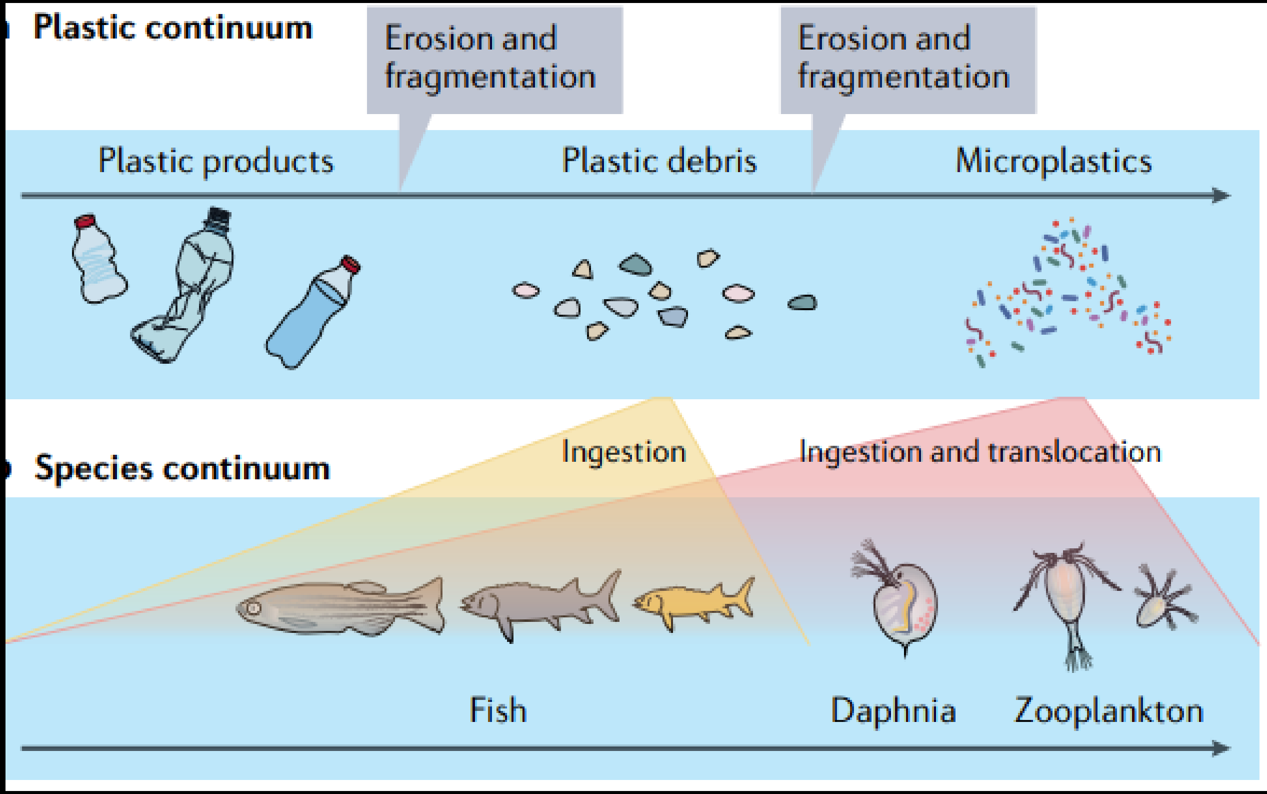


Law et al., Sci. Adv., 2020

- Plastics waste input to the ocean, and China contributed the largest in the world in 2010 (one year)
- The United States' contribution was the highest in the world after accounting for illegally dumped and exported waste in 2016 (one year)

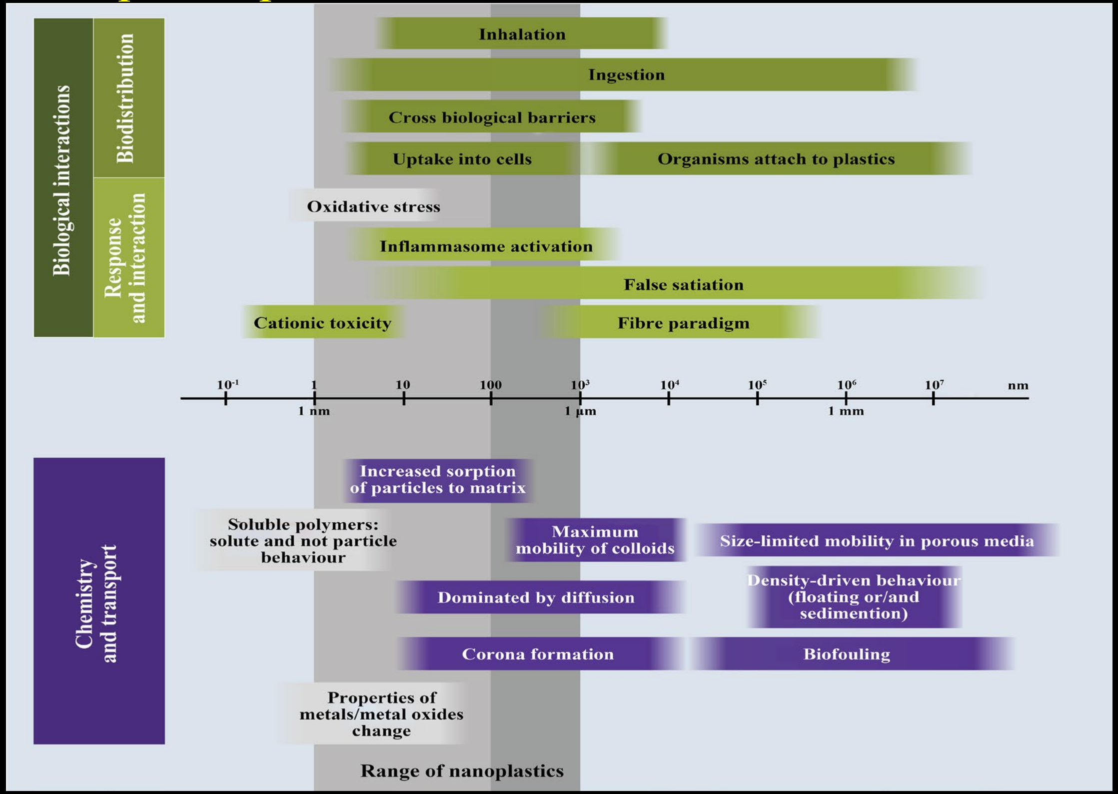
Small plastics should be better understood

Interactions of plastics with organisms



Koelmans et al., Nat. Rev. Mater., 2021

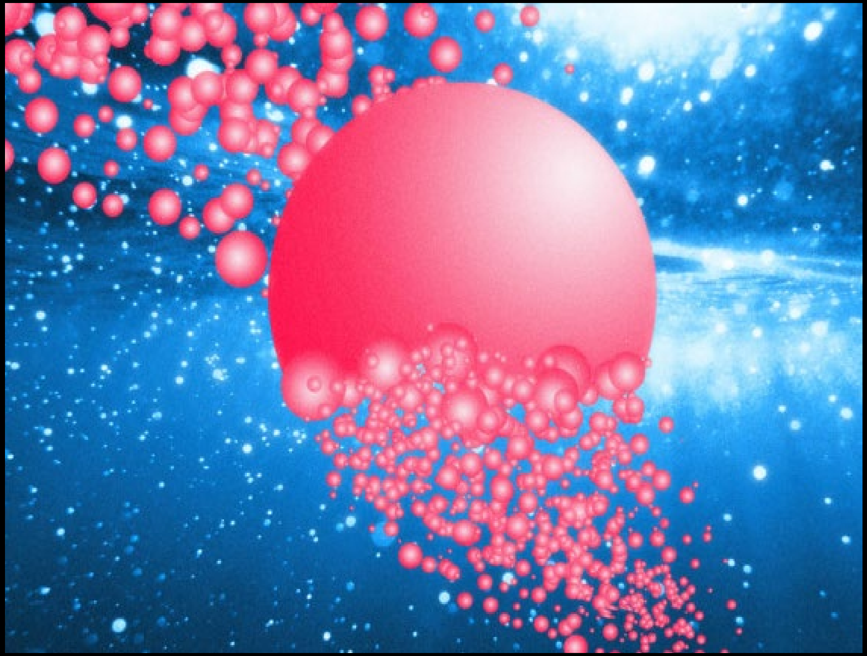
Effect of particle size on the biological interactions and transport of plastic wastes



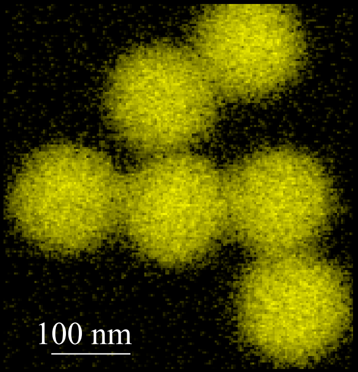
Mitrano et al., Nat. Nanotechnol., 2021

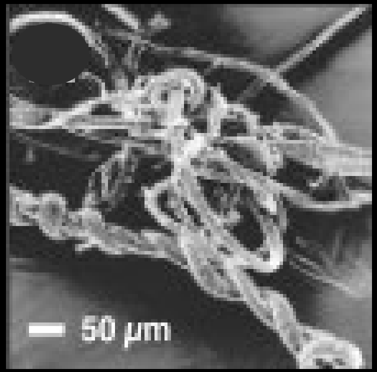
- Small plastics are more bioavailable and may trigger interactions with a variety of species, leading to more ecological risk
- Small plastics are highly polydisperse in physical properties and heterogeneous in composition, leading to longer transport distance in the environment

What are microplastics?



Macroplastics produce microplastics and nanoplastics





Nanoplastics (NPs) | 1 µm | Microplastics (MPs) | 5 mm | Macroplastics

Wagner et al., Nat. Nanotechnol., 2019
Thompson et al., Science, 2004

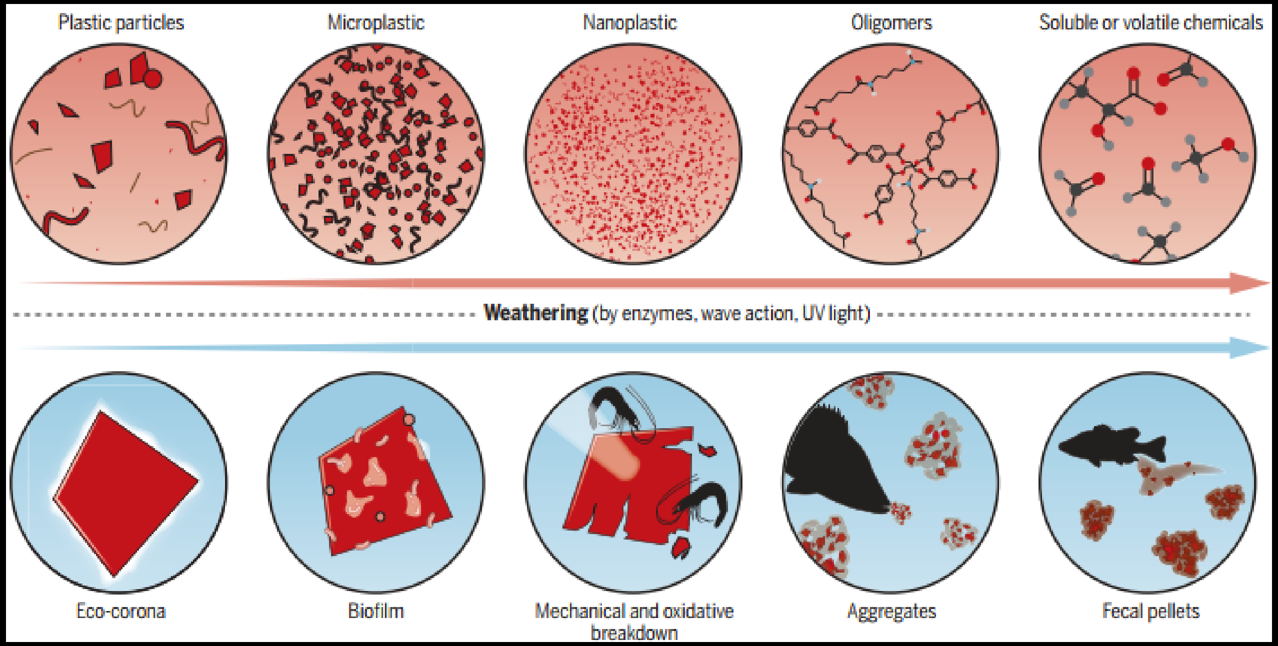
- In 2004, the term "microplastics" was first used
- In 2008, microplastics were defined as particles less than 5 mm in size
- Definition of nanoplastics is still under debate: 1-1000 nm *vs.* 1-100 nm

How are microplastics generated?



Primary microplastics

- Facial-cleansers and cosmetics
- Vectors for drugs
- Virgin plastics production pellets



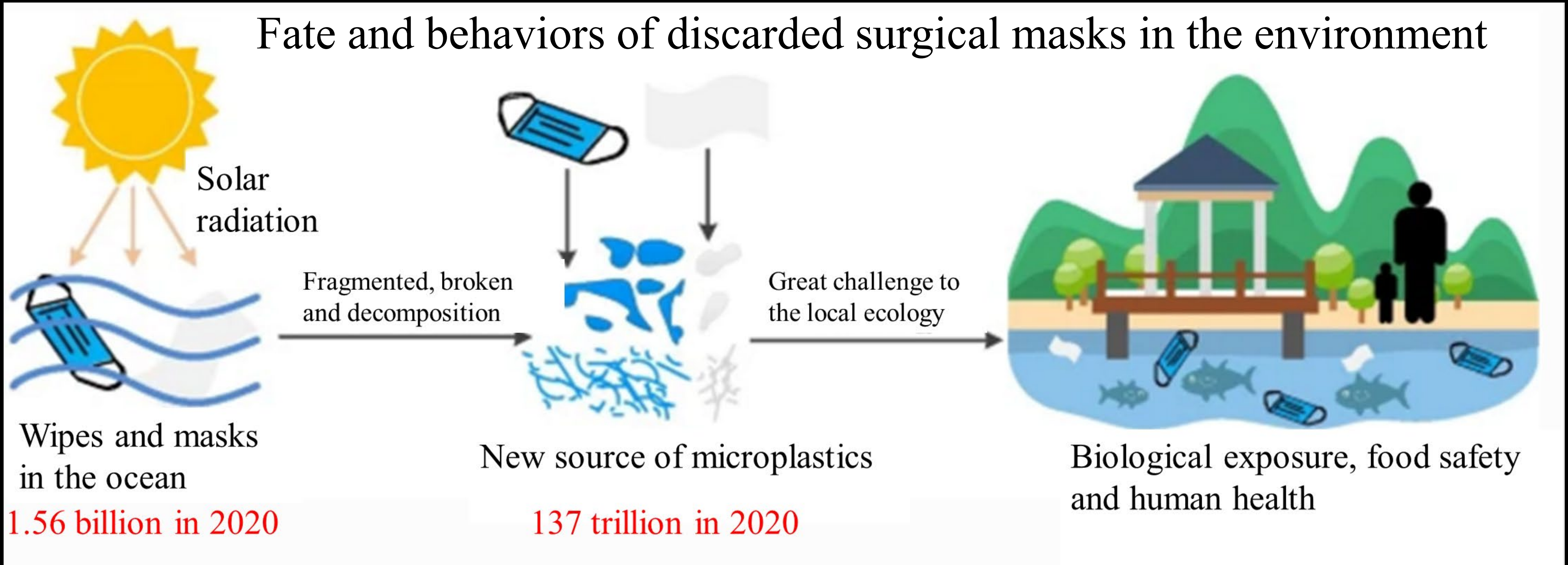
MacLeod et al., Science, 2021


DeFrancesco et al., Nat. Biotechnol., 2020

Secondary microplastics

- Physical (e.g., wind, wave)
- Chemical (e.g., UV)
- Biological (e.g., microorganisms)

Surgical masks: a new source of microplastics



Hu et al., Environ. Sci. Pollut. Res., 2022; Sun et al., Environ. Sci. Technol. Lett., 2021

- Disposable surgical masks lead to the increase of microplastics (137 trillion in 2020) in the marine environment through degradation and fragmentation
- Disposable surgical masks are becoming a new source of microplastics in the marine environment

Concerns are raised about the microplastics in the environment

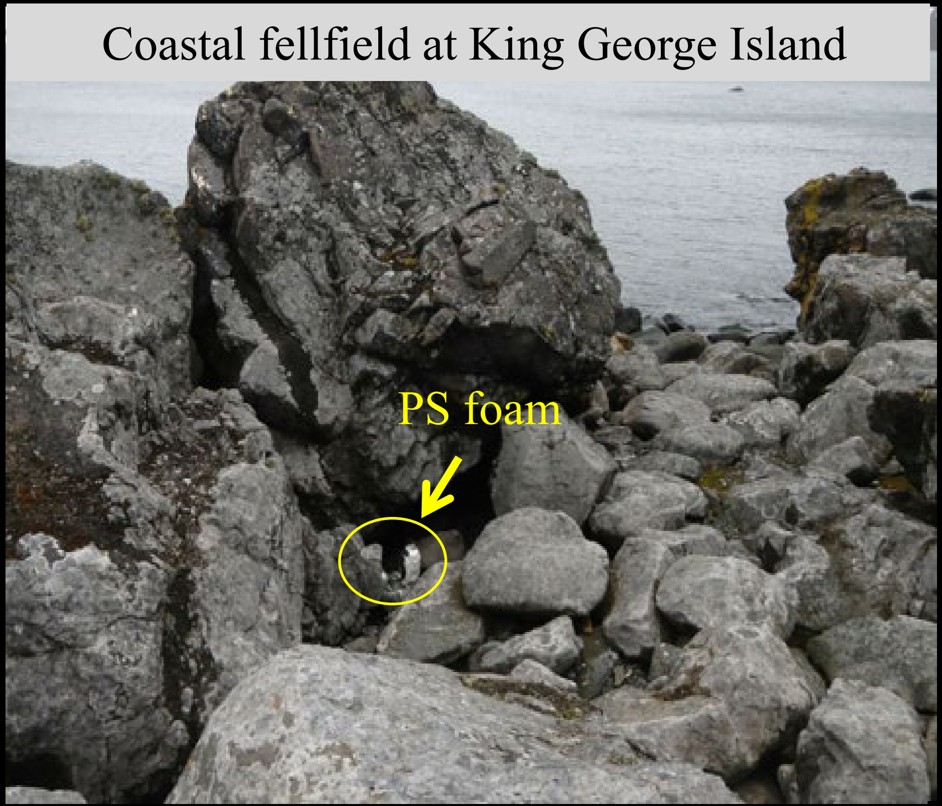
The following issues are addressed in this presentation:

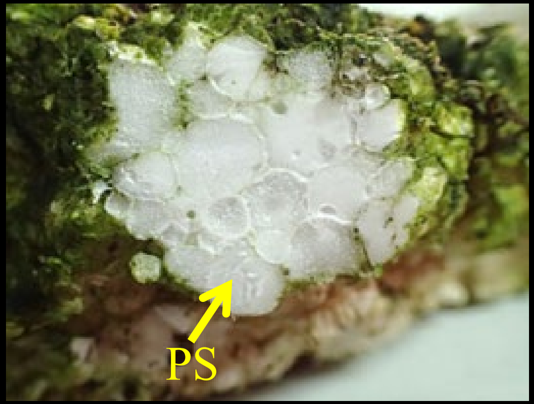
- What are the distribution and environmental behavior of microplastics in the environment?
- What are the toxicological mechanisms of microplastics, and the role of eco-corona/biofilm?
- How do microplastics pose risk to human health?

II. Distribution of microplastics

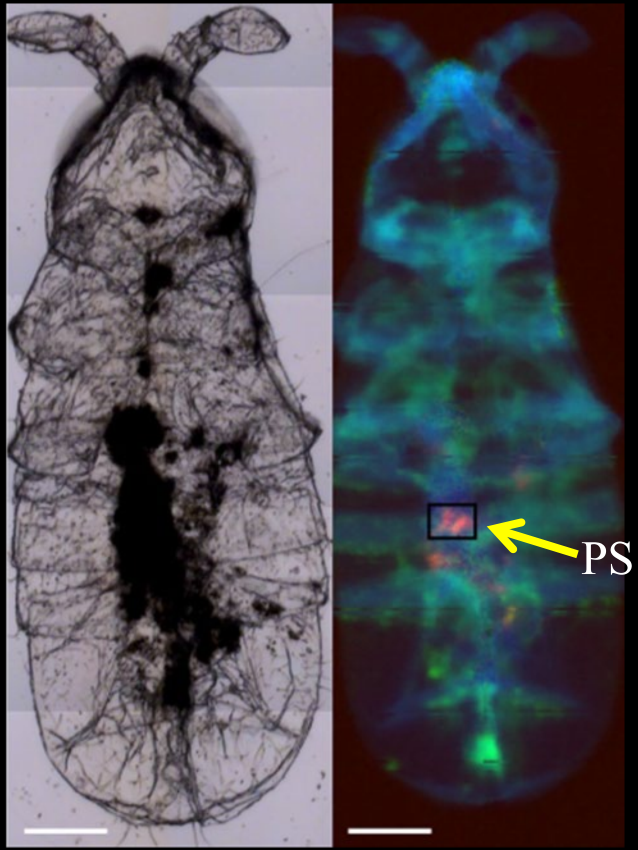
Microplastics contaminate the most remote regions

Microplastics in Antarctic Pole





Antarctic collembolans

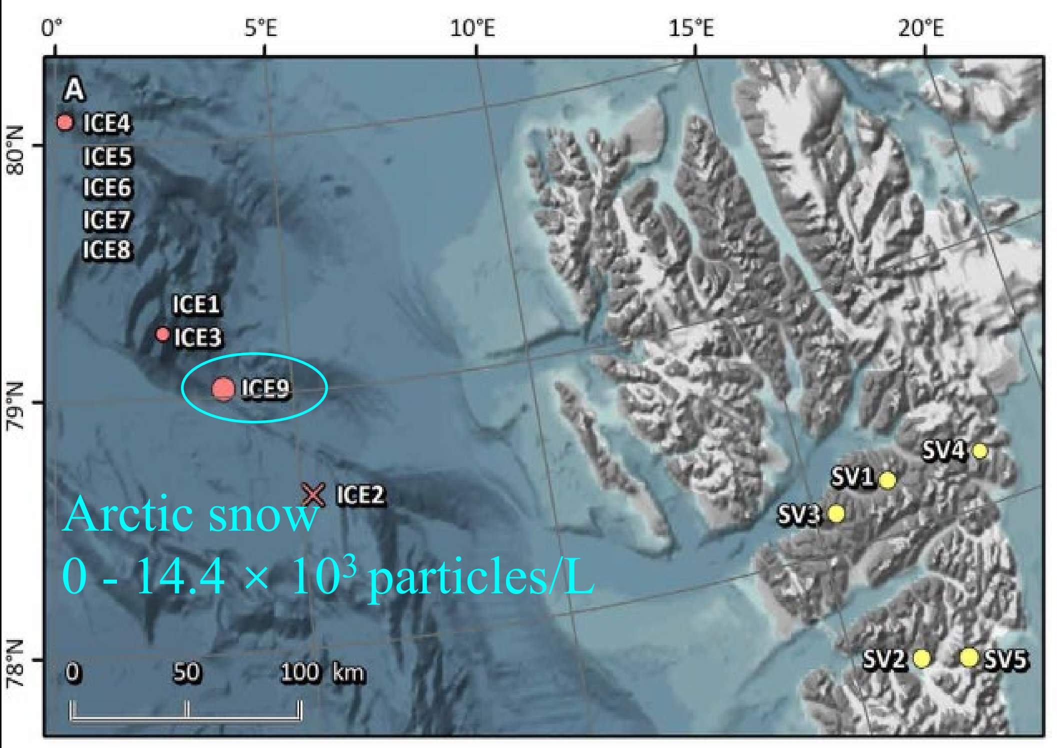


Bergami et al., Biol. Lett., 2020

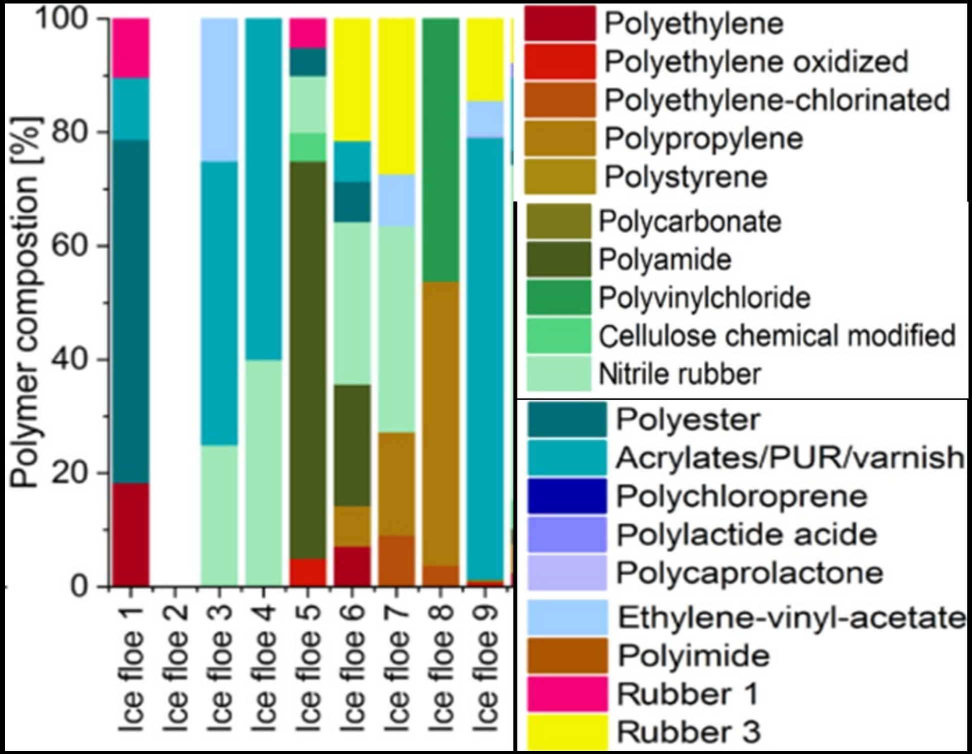
- Microplastics were detected in the Antarctic terrestrial environment and Antarctic collembolans, and the detected type was polystyrene (PS) foam

Microplastics in the Arctic Pole

Map of sampling locations for snow



Relative composition of microplastics

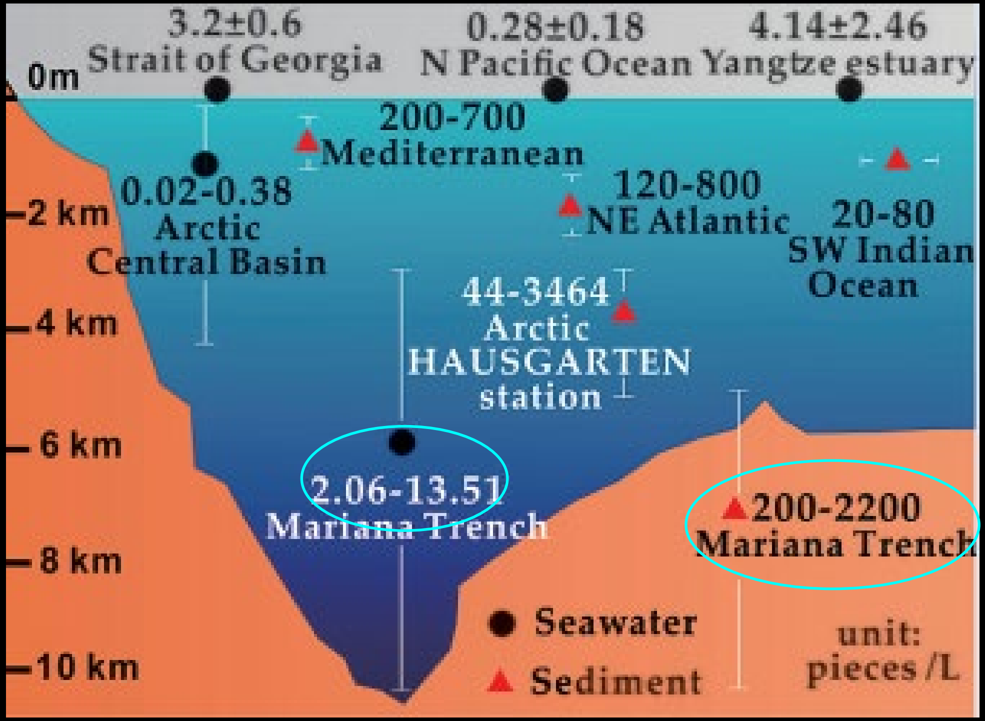


Bergmann et al., Sci. Adv., 2019

- The size of microplastics detected in Arctic ranged 11-475 μm, and the highest concentration in snow was 14.4×10^3 particles/L
- PS, polyvinyl chloride (PVC), polycarbonate (PC), polylactic acid (PLA), and polyimide (PI) occurred exclusively in Arctic snow

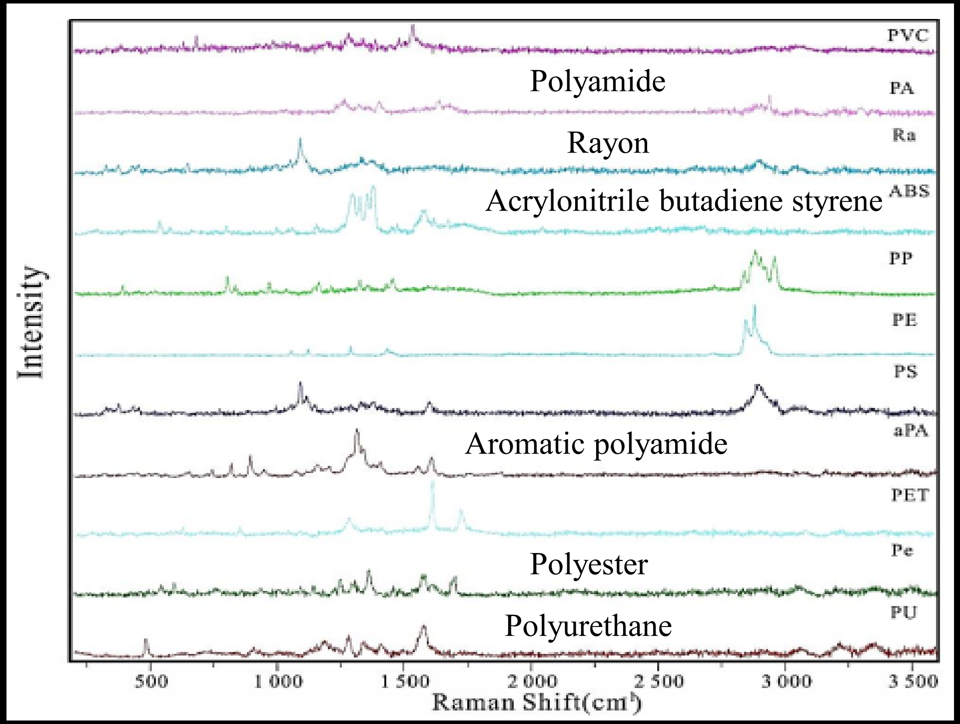
Microplastics in the deepest part of the world's ocean

Microplastics in Mariana Trench



Depth: 6,000-11,000 m

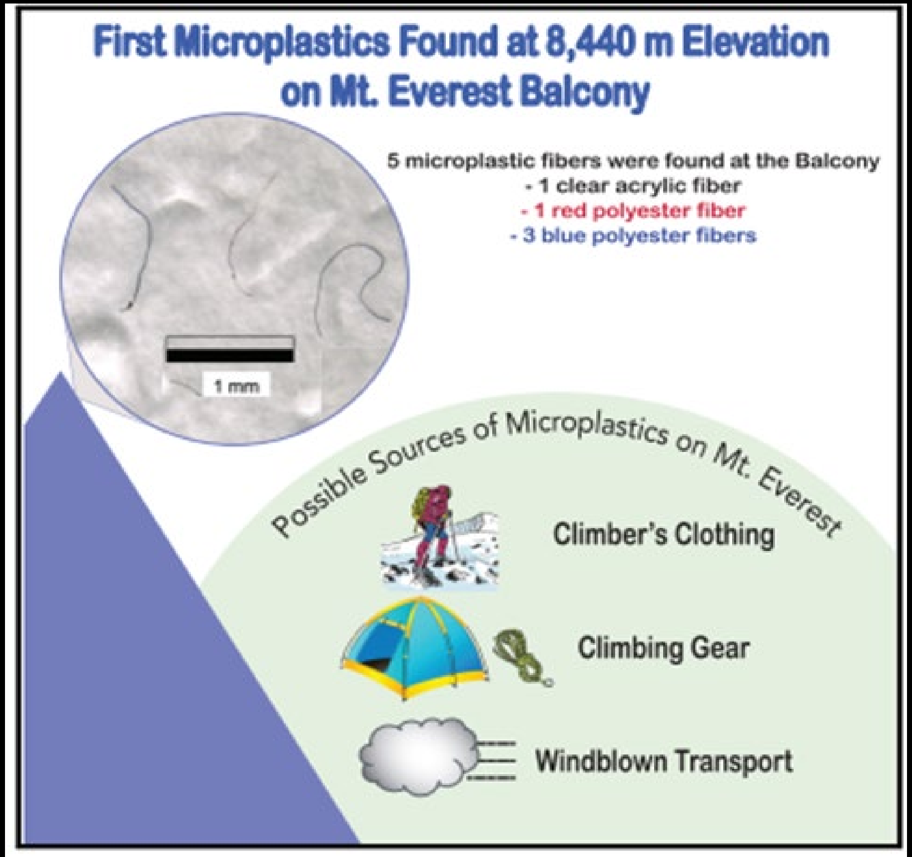
Raman spectra analysis

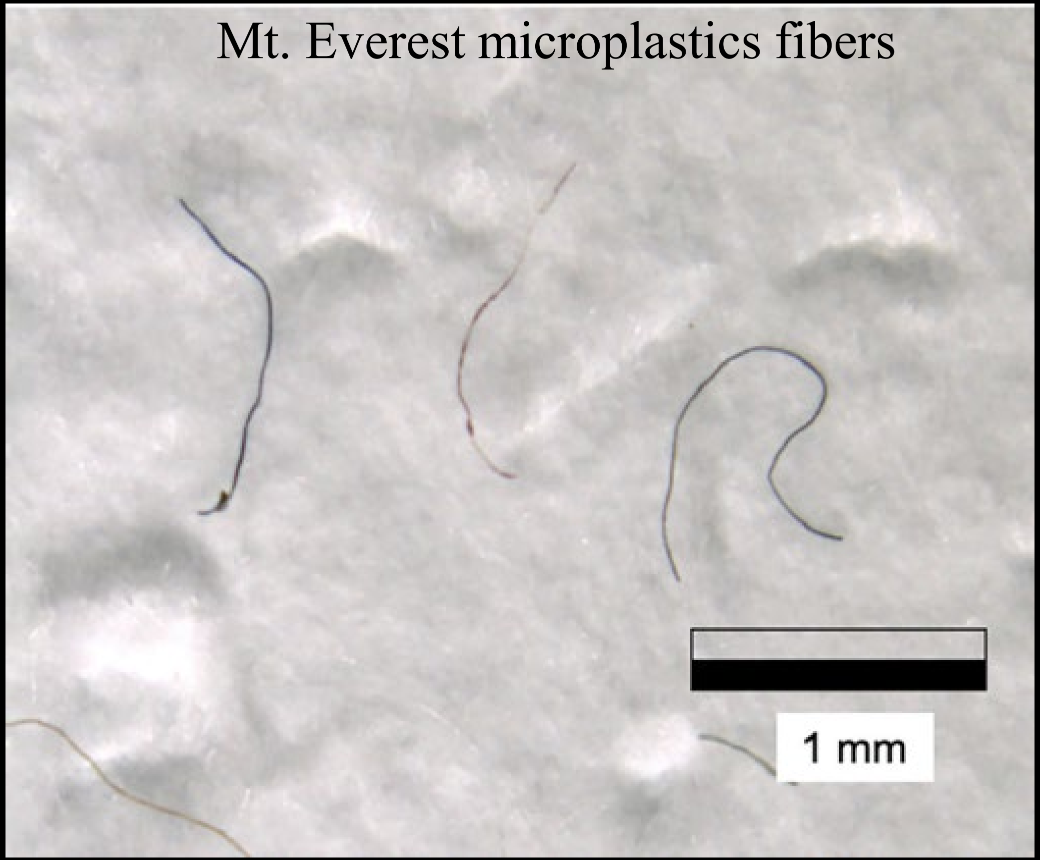


Peng et al., Geochem. Persp. Let., 2018

- Microplastics abundances in hadal sediments (200-2,200 particles/L) were higher than those in hadal bottom seawaters (2.06-13.51 particles/L)
- Eleven different microplastic types were identified from the Mariana, and the length of microplastics in seawater (1-3 mm) was longer than those in sediment (0.1-0.5 mm)

Microplastics on Mount Everest



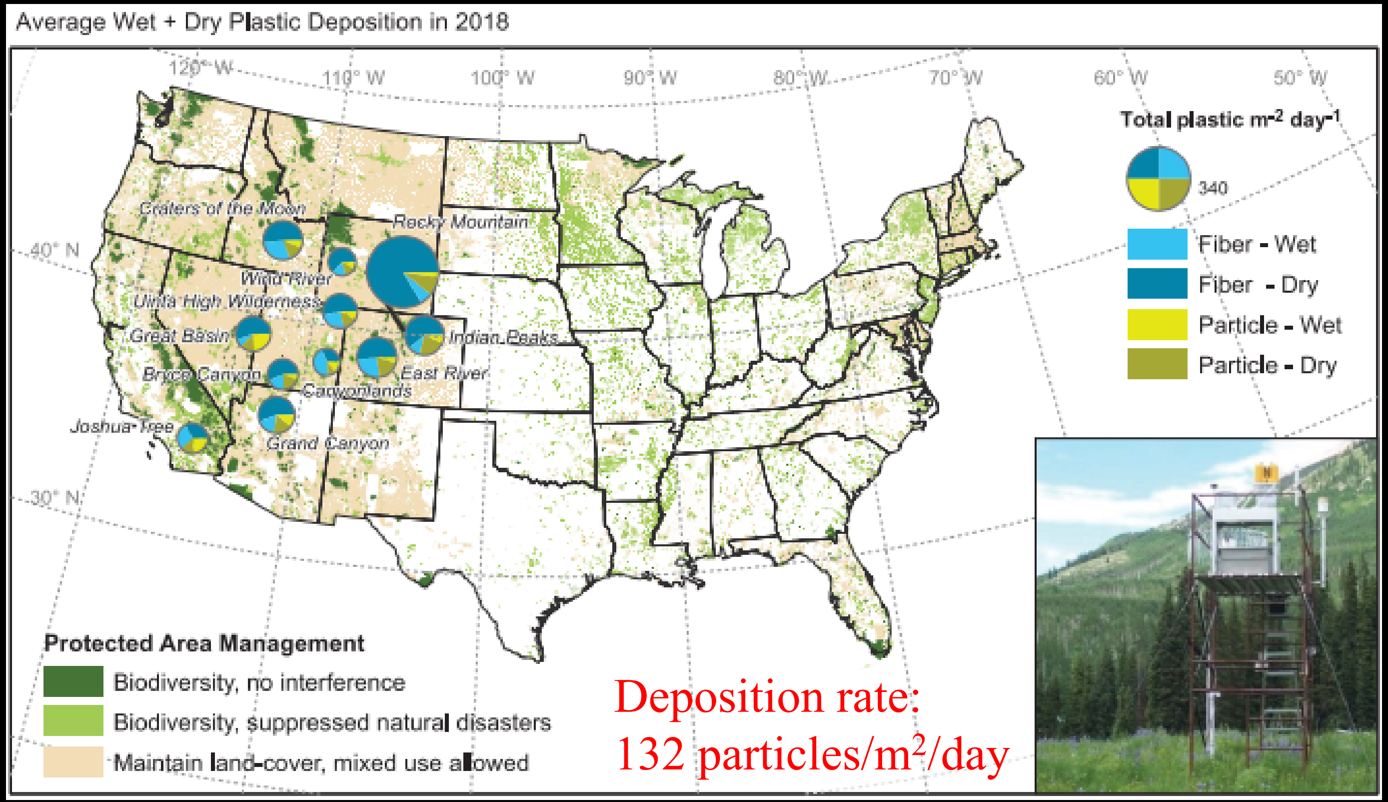


Napper et al., One Earth, 2020

- Five microplastics fibers were found at the Balcony (8,440 m), including 1 clear acrylic fiber, 1 red polyester fiber and 3 blue polyester fibers, probably released from climber's clothing and climbing gear

Microplastics deposition in remote U.S. conservation areas

Microplastics deposition in 11 National parks and wilderness areas in U.S.

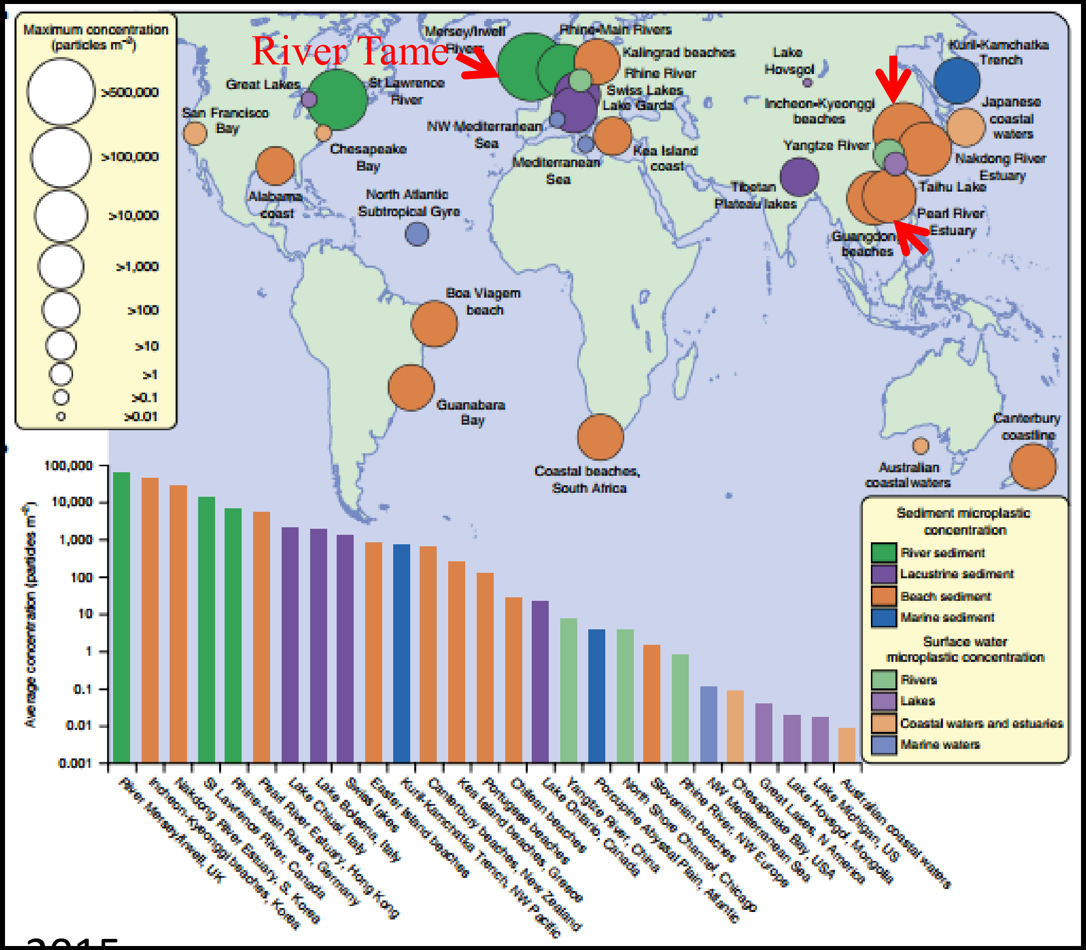


Brahney et al., Science, 2020

- Microplastics were distributed in U.S. protected areas (98% of atmospheric samples)
- Microfibers (20 µm-3 mm) made up most of the synthetic material
- Urban centers and resuspension from soils or water are principal sources for wet-deposited microplastics
- Long-range or global transport leads to the smaller size of microplastics under dry conditions

Distribution of microplastics in the environment

Microplastics in the surface water and sediments of the world

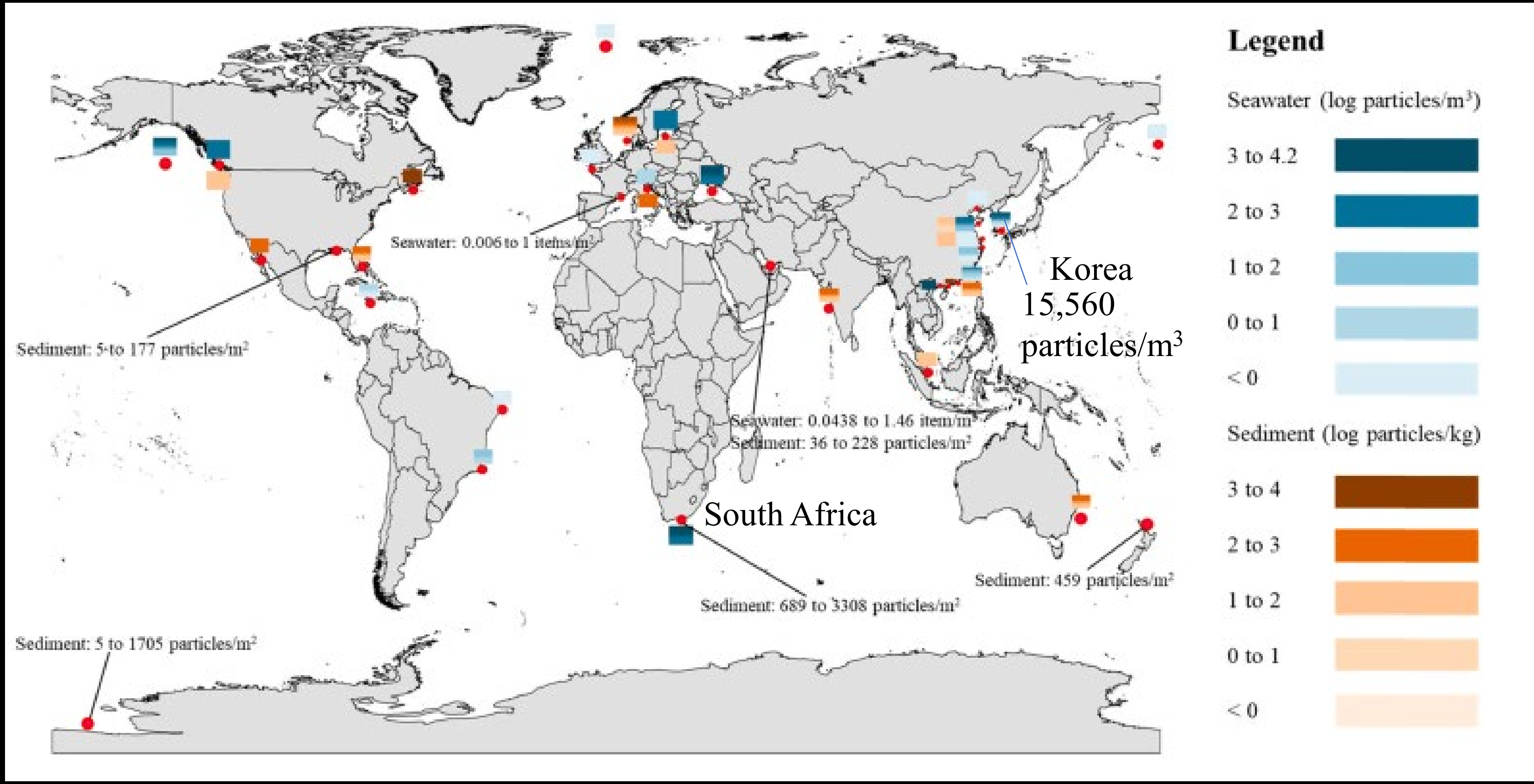


The first global microplastics map

- The highest concentration (~517,000 particles/m^2) was in the sediments of River Tame, UK
- The top 9 ranked hotspots were located within the world's most populous urban environments, such as Seoul, Hong Kong, and Guangdong

Hurley et al., Nat. Geosci., 2019

Microplastics in marine environments (seawater and sediment)

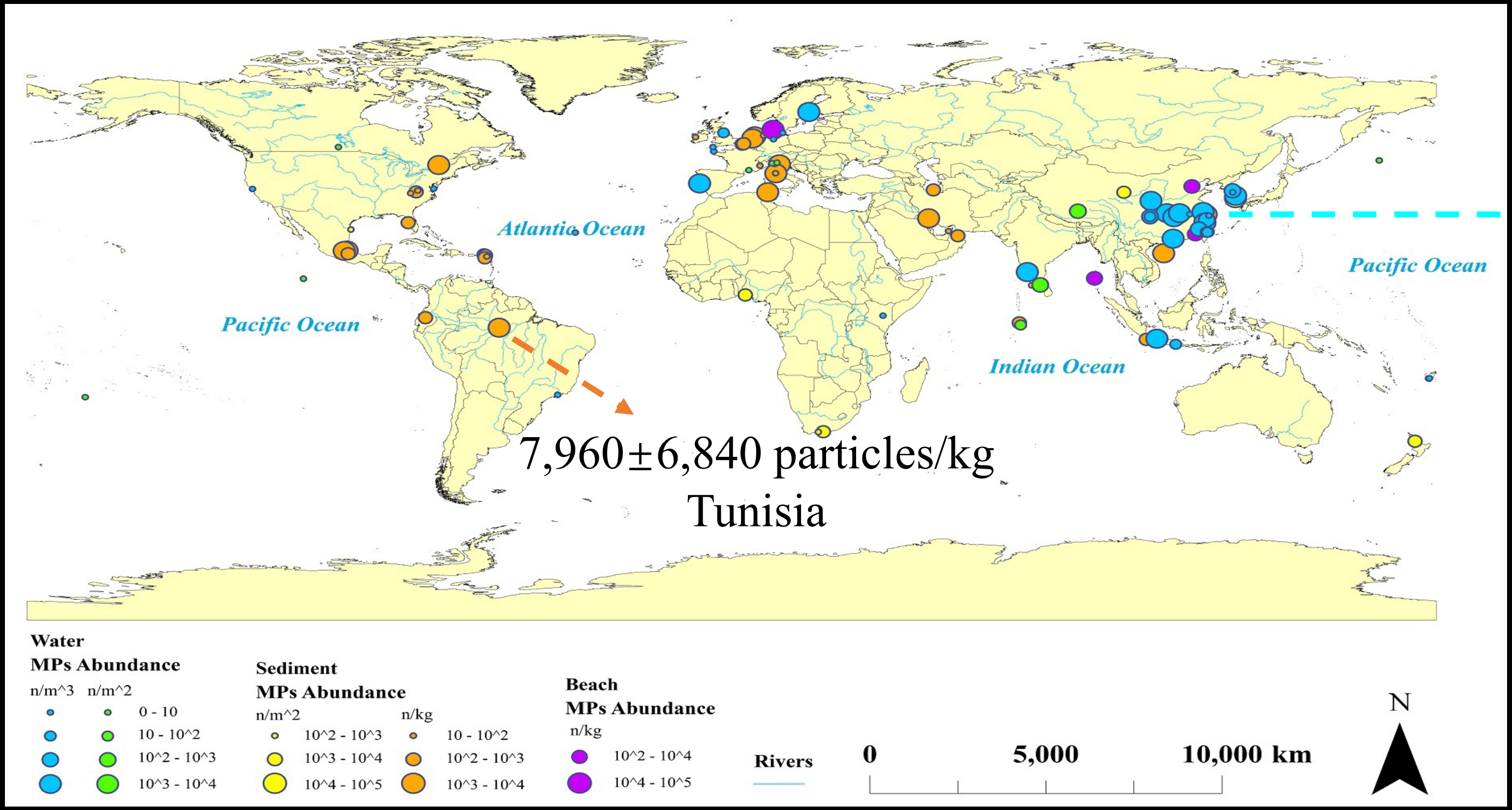


Highest concertation
Seawater: 15,560 particles/m^3 in Korea
Sediments: 2,000–8,000 particles/kg in Canada; 689-3,308 particles/m^2 in South Africa

Wang et al., J. Hazard. Mater., 2021

- Microplastics are found in oceans all over the world, and the concentrations in seawater and sediments could vary by 4 orders of magnitude
- Microplastics pollution in seawater or sediment is very severe in some areas (e.g., China, Canada, Korea)

Microplastics in inland water, sediments, and beaches



Wang et al., Environ. Sci. Technol., 2021

Highest concertation

Inland water: Yangtze River basin 500 to 3,100 particles/m^3 (middle-lower)
1,597 to 12,611 particles/m^3 (Three Gorges Reservoir)

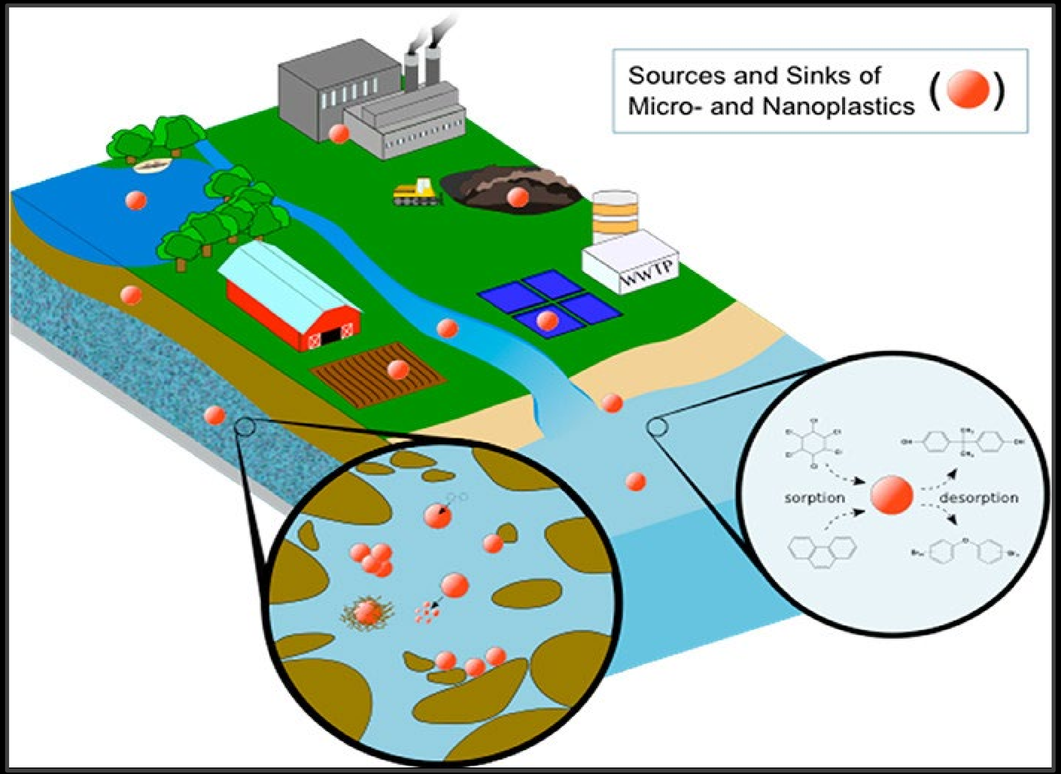
Beach: 285,673 particles/m^2 in South Korea

Inland sediments: 7,960±6,840 particles/kg in Tunisia

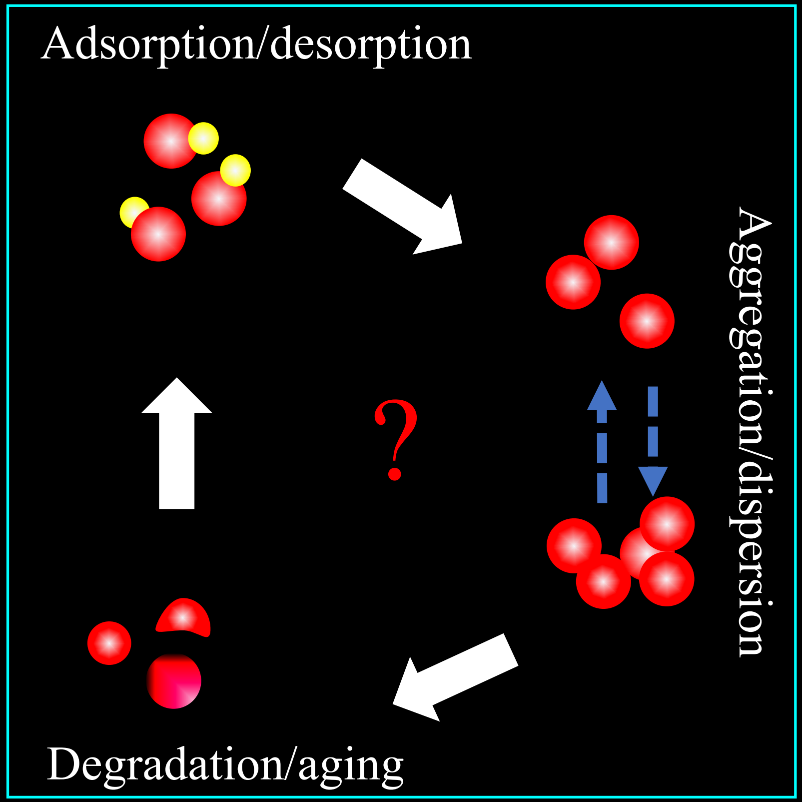
- The highest microplastics concentration in lake sediments and inland waters located in Tunisia and Yangtze River, respectively
- Microplastics concentration in inland water, sediments and beaches could vary by 4, 4, 5 orders of magnitude, respectively

III. Environmental behavior of microplastics

Environmental processes in aquatic environment



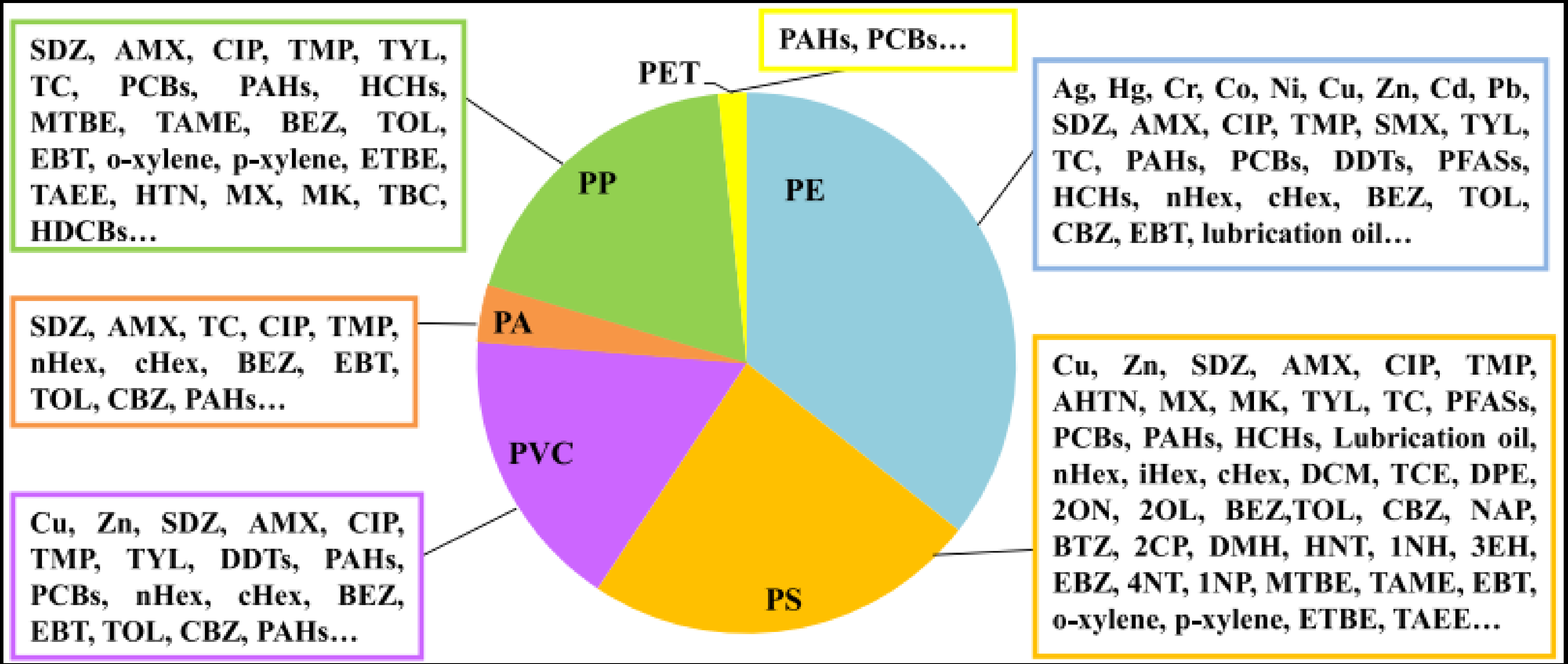
Olubukola et al., Environ. Sci. Technol., 2018



- Adsorption/desorption, aggregation/dispersion and transformation (degradation/aging) are the most important environmental processes of microplastics
- Aggregation behavior would greatly change the transport of microplastics
- Degradation affects aggregation and adsorption ability of microplastics

Adsorption behavior of microplastic in the environment

Current research on adsorption of pollutants by microplastics



Types of pollutants

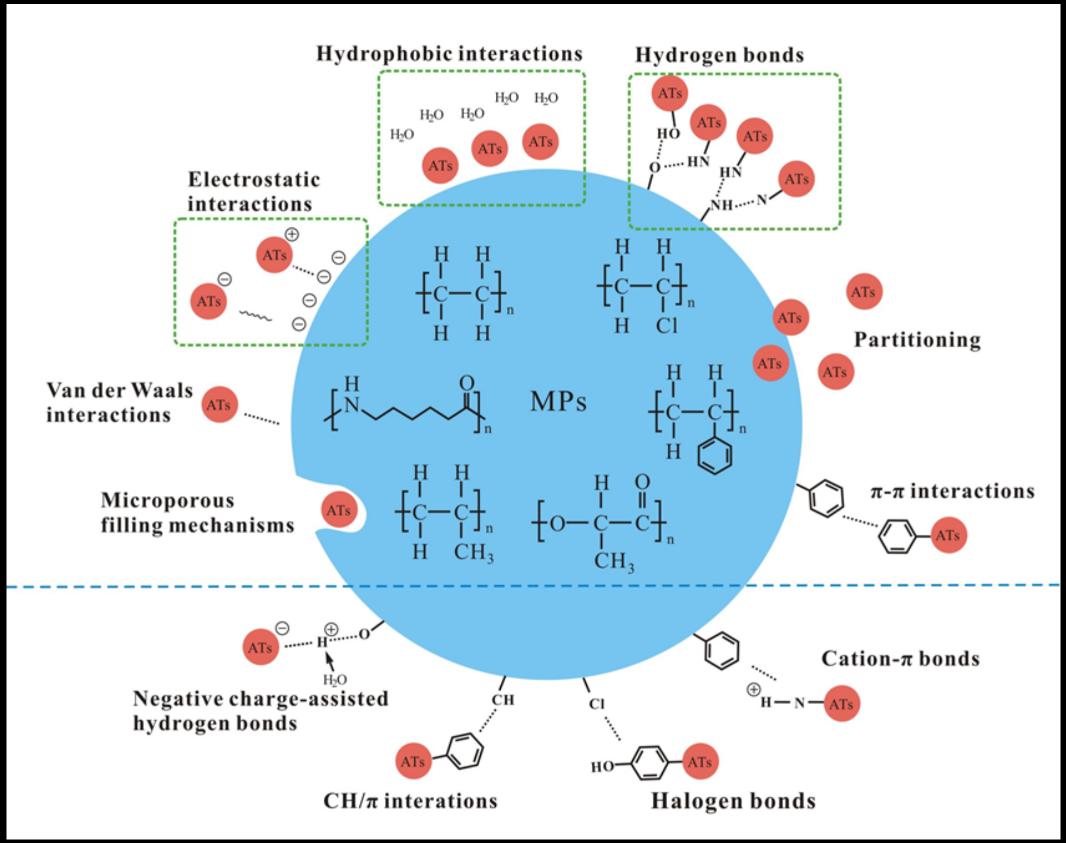
- Organic pollutants
- Heavy metals

Guo and Wang, Mar. Pollut. Bull., 2019

- The most frequently-studied microplastics are PE, PS, PVC, and PP
- At room temperature, PE being vert rubbery showed higher adsorption capacities for organic pollutants than PS and PVC (glassy state), due to the contribution of partitioning
- Microplastics properties (e.g., molecular structure, specific surface areas, crystallinity, and polarity) could influence the adsorption

Adsorption mechanisms

Adsorption mechanisms of antibiotics on microplastics



Wang et al., Environ. Sci. Technol., 2021

Adsorption mechanisms

- Hydrophobic interactions
- Hydrogen-bonding interactions
- Electrostatic interaction

Main forces

- Van der Waals
- Partitioning
- π-π interactions
- Halogen bonds
- Cation-π bonds
- CH/π interactions
- Negative charged-assisted hydrogen bonds

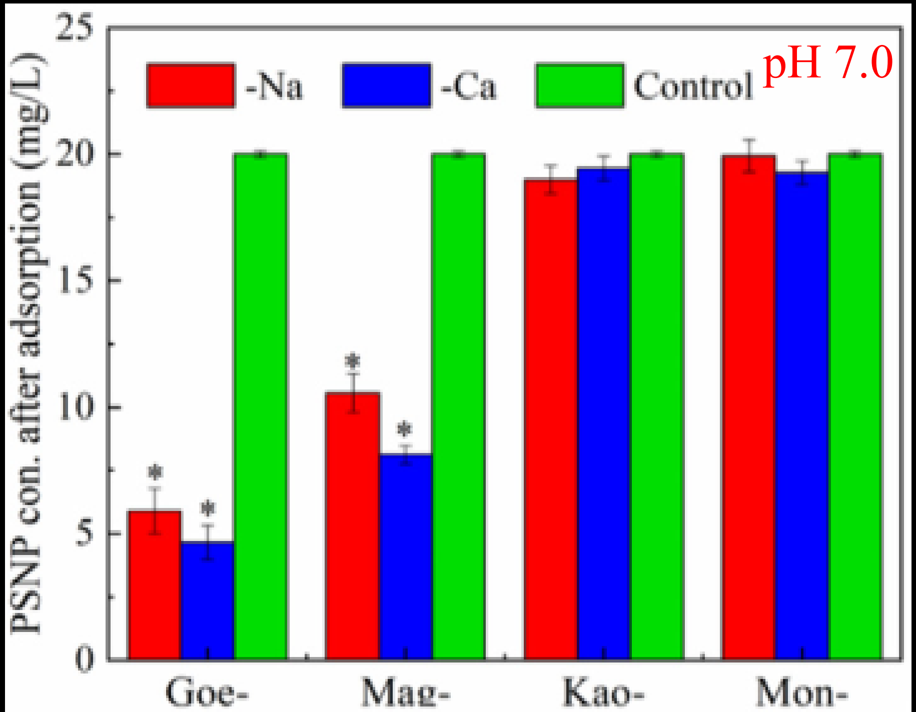
Future studies can focus on these mechanisms

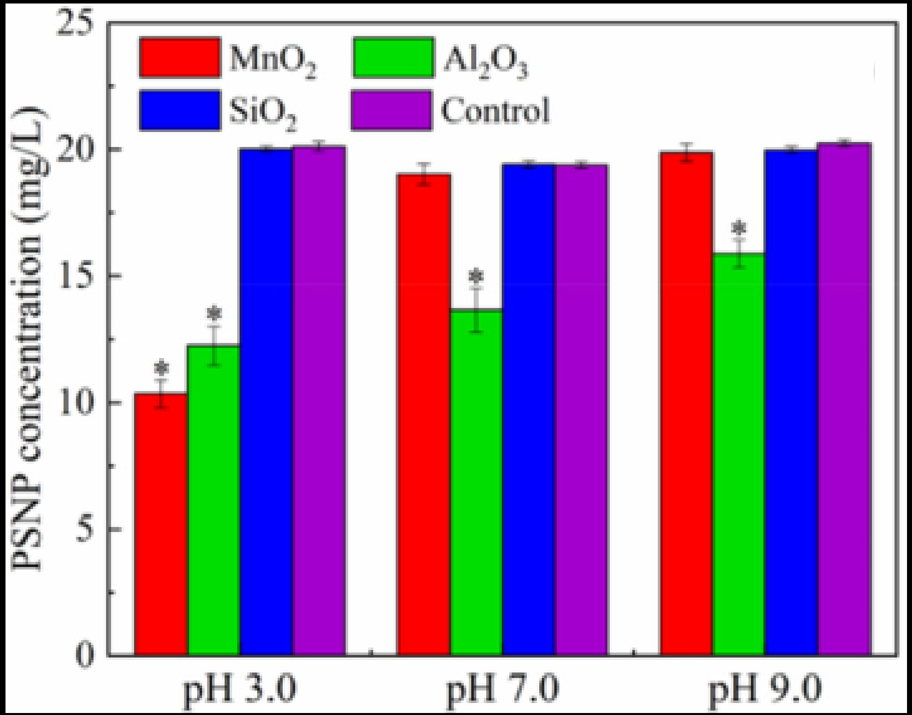
- Hydrophobic interactions, hydrogen-bonding interactions and electrostatic interaction were confirmed as the important forces during microplastics adsorption antibiotics
- Future studies can focus on the relative contributions of individual mechanisms during adsorption

Aggregation of microplastic in the environment

Microplastics-mineral heteroaggregation

Interactions of PS nanoplastics with different kinds of minerals





Zhang et al., Water Res., 2020

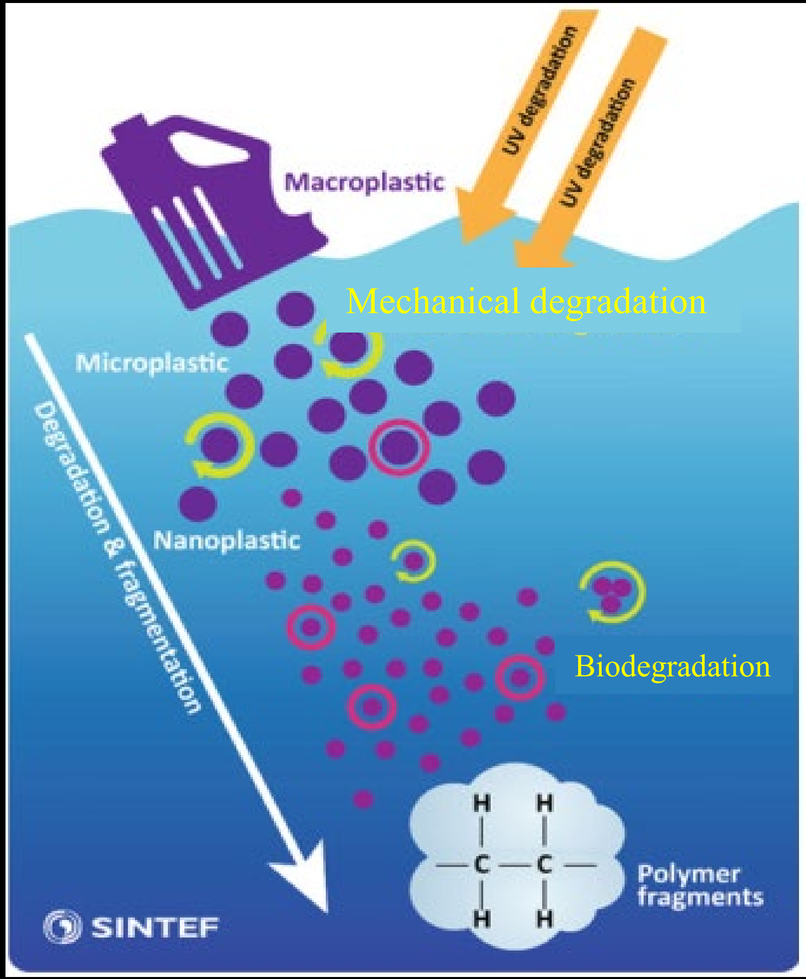
Positive charge (+): Goethite, magnetite, Al_2O_3; Negative charge (-): Kaolinite, montmorillonite, SiO_2, MnO_2

- Heteroaggregates could form between microplastics and positively charged minerals due to electrostatic interaction
- Goethite showed higher heteroaggregation with PS than magnetite, due to the formation of hydrogen bonding

Aging/degradation of microplastics in the environment

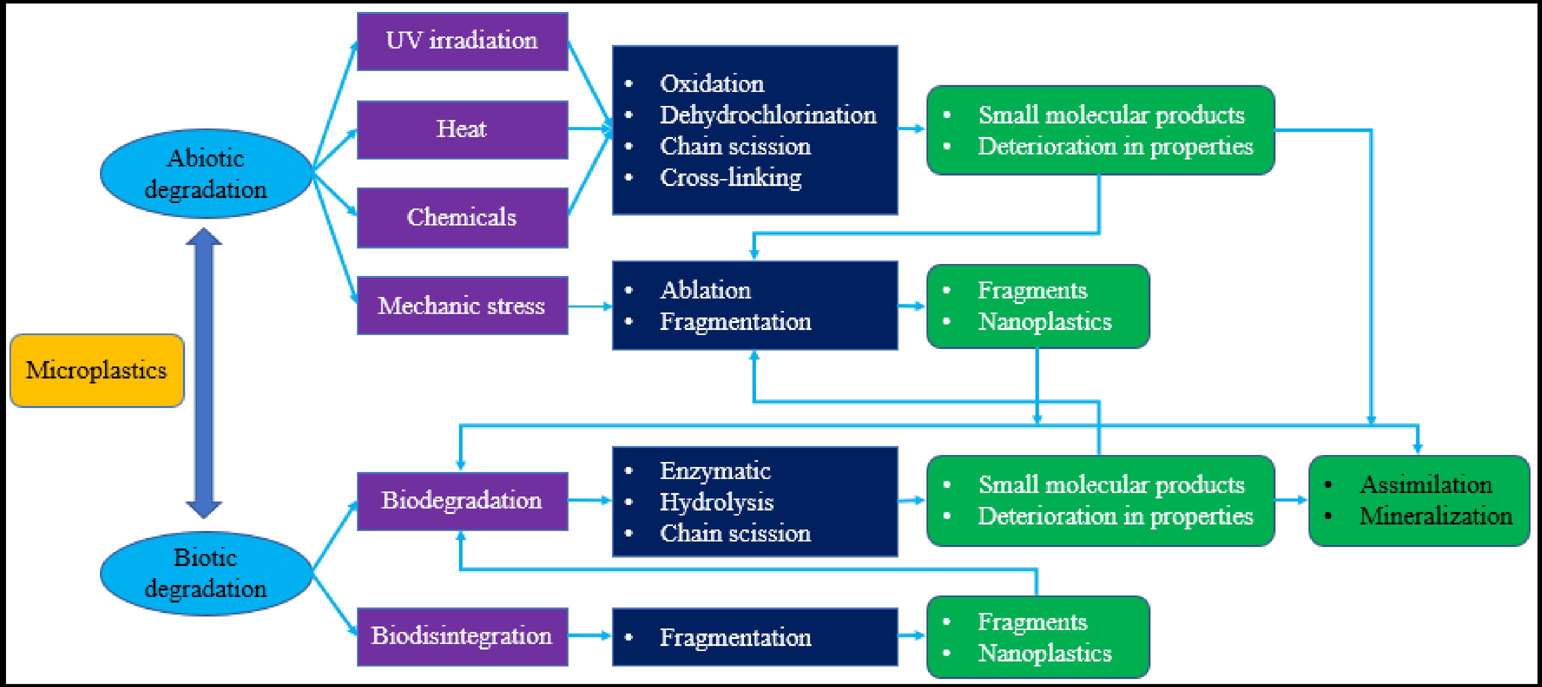
Degradation processes and pathways of microplastics

Degradation processes



Booth et al., Norwegian Environment Agency, 2018

General processes involved in the degradation of microplastics

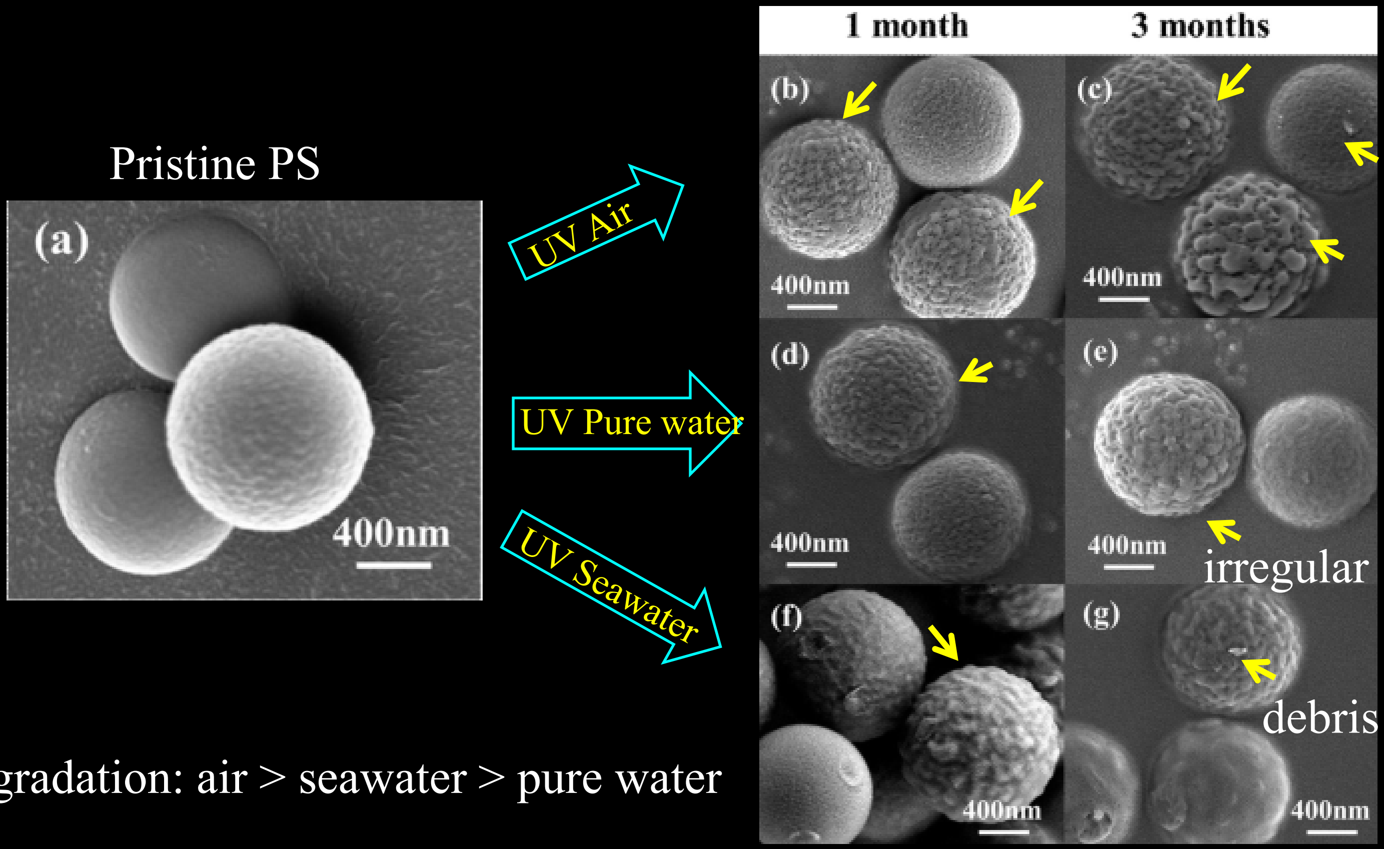


Modified from Zhang et al., Environ. Pollut., 2021

- UV degradation is the most important process for microplastics transformation
- Hydrolysable polymers (e.g., polyethylene terephthalate, PET) are more susceptible to biodegradation due to the presence of extracellular hydrolases in the organisms

UV-induced microplastics degradation

PS microplastics under UV irradiation in air, pure water and seawater



Degradation: air > seawater > pure water

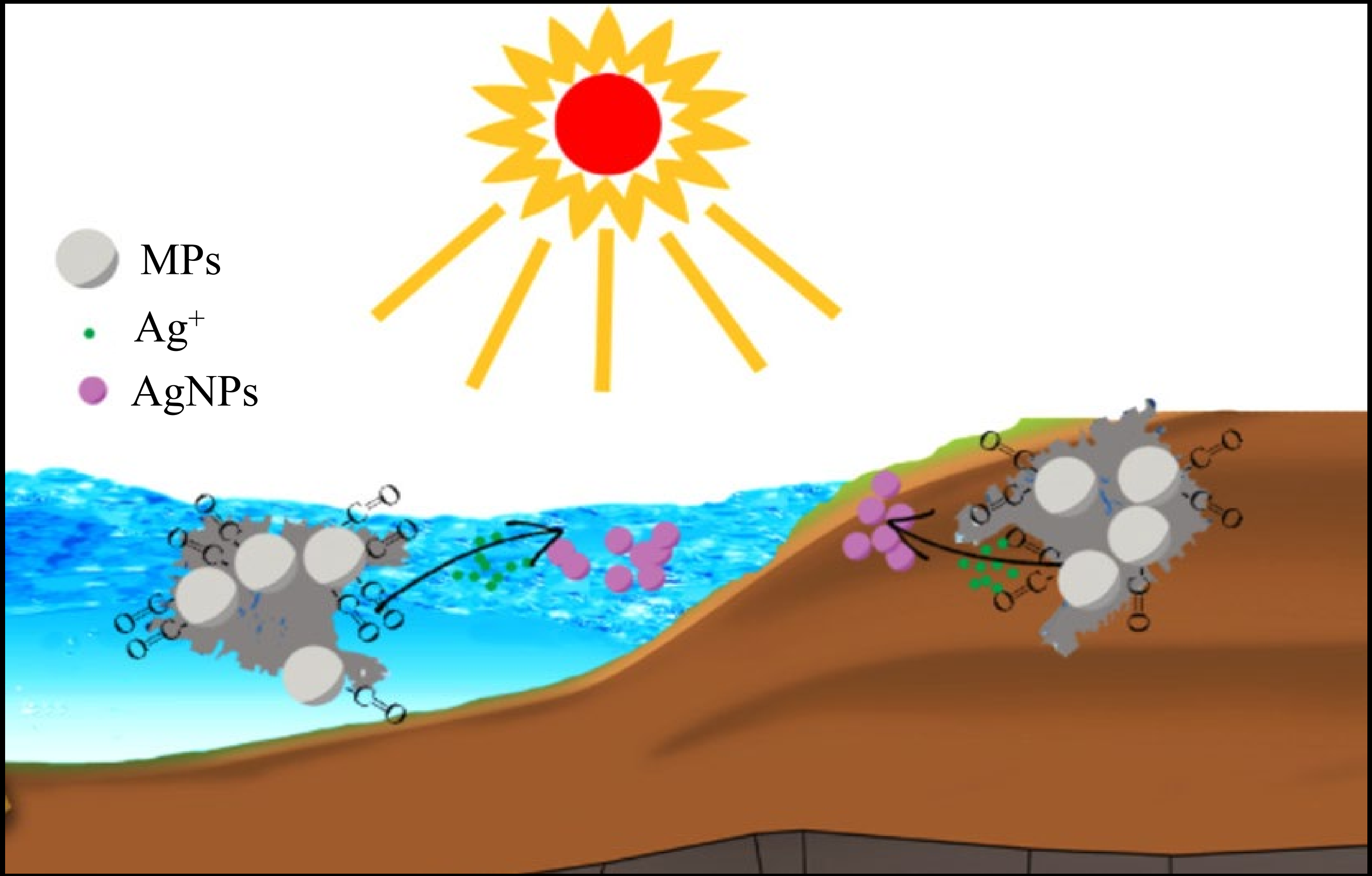
Change on physicochemical properties of typical microplastics after aging

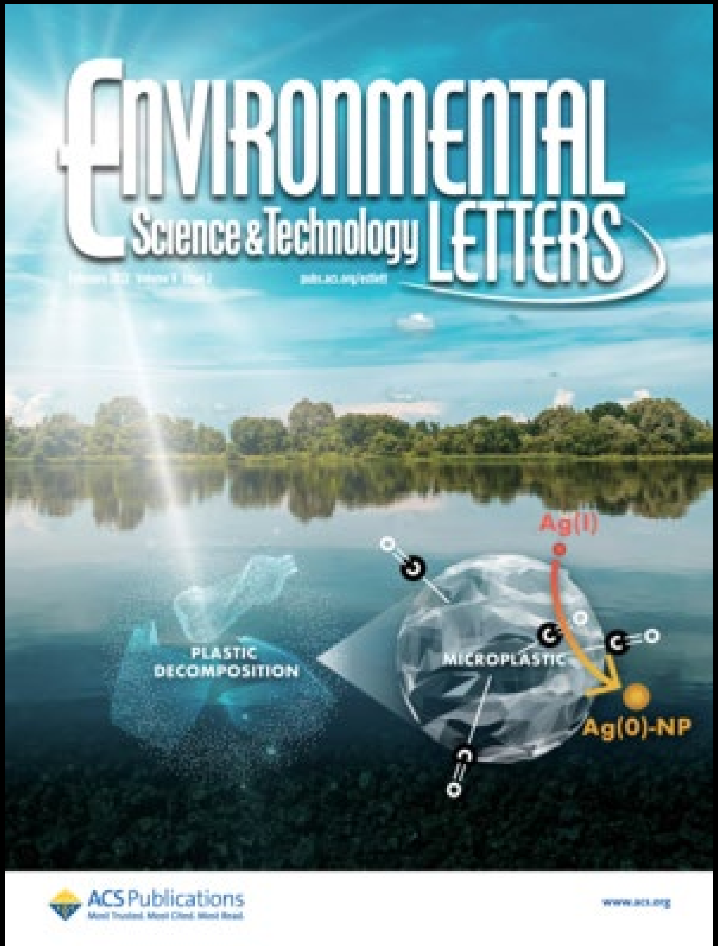
- Surface becomes rough
- Generates pores and debris
- Crystallinity increases (PS, PE), decreases (PP)
- Oxygen-containing functional groups (O/C, carbonyl index) increase
- Hydrophilicity increases

Mao et al., J. Hazar. Mater., 2020

- Microplastics degradation in air was much stronger than waters due to the higher utilization rate of UV light
- The aging degree in seawater is higher than that pure water, but the specific mechanism was not investigated

Weathered microplastics induce silver nanoparticle formation from Ag^+



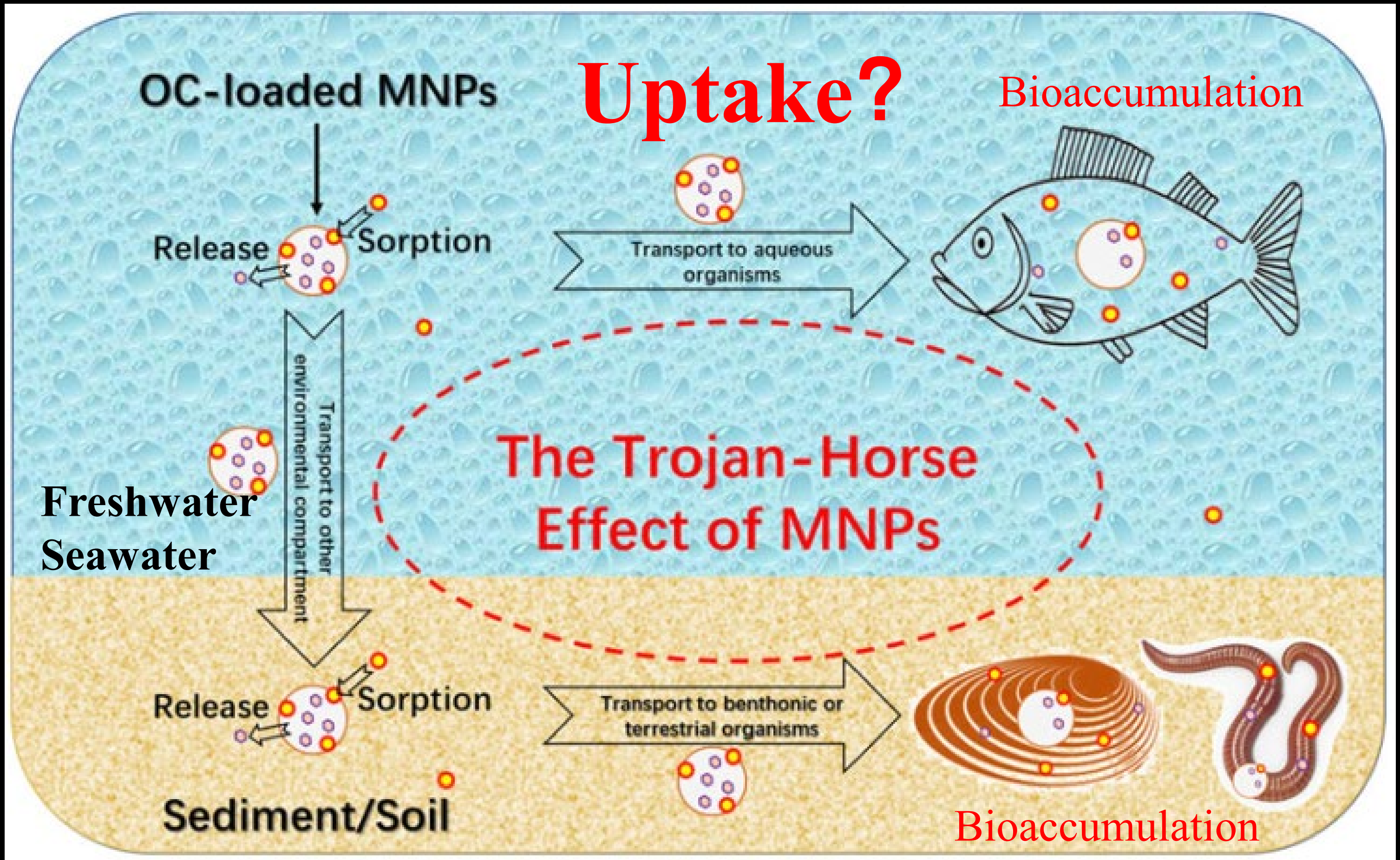


Huang et al., Environ. Sci. Technol. Lett. 2022

- Carbonyl groups including aldehydes on weathered PS act as a key determinant for Ag(I) reduction
- This study points out a previously unrecognized pathway of natural Ag(0) nanoparticles formation

IV. Toxicity of microplastics

Uptake and toxicity of microplastics in organisms

Microplastics →  → Toxicity?

Zhang et al., Crit. Rev. Environ. Sci. Technol., 2020

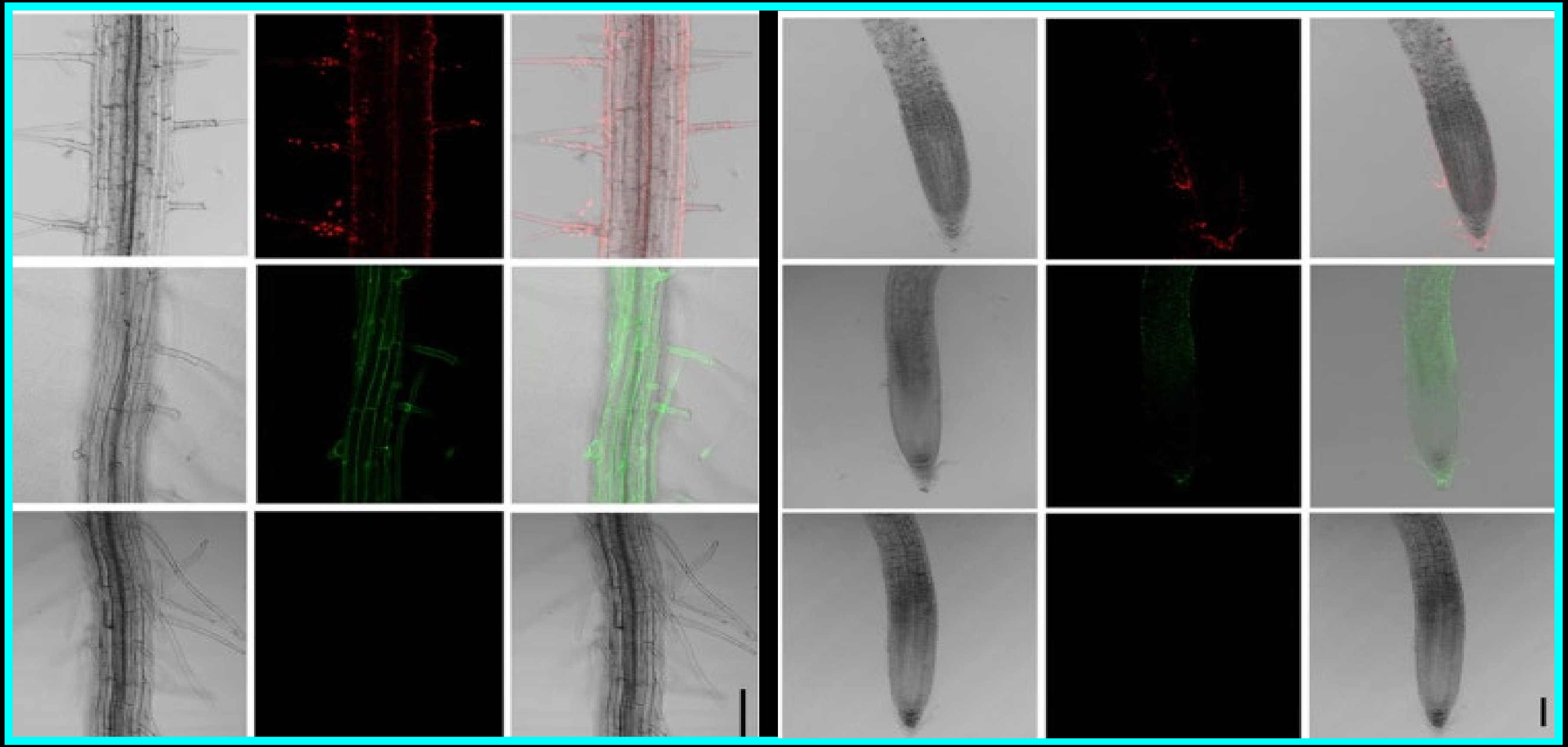
- Microplastics could be taken up by terrestrial, freshwater and marine organisms, and exhibited toxicity

Uptake of microplastics in the terrestrial plants

PS nanoplastics accumulated in *Arabidopsis thaliana*

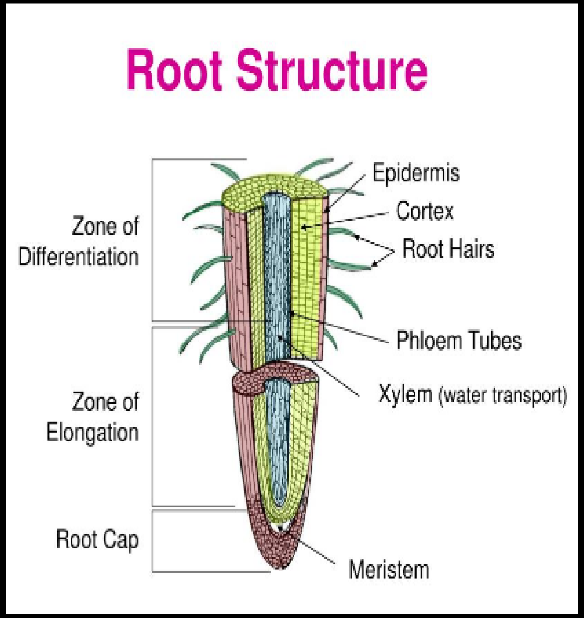
Maturation zone | Nanoplastics | Merged | Root tip | Nanoplastics | Merged

PS-COOH (red) | PS-NH_2-F (green) | Control



Sun et al., Nat. Nanotechnol., 2020

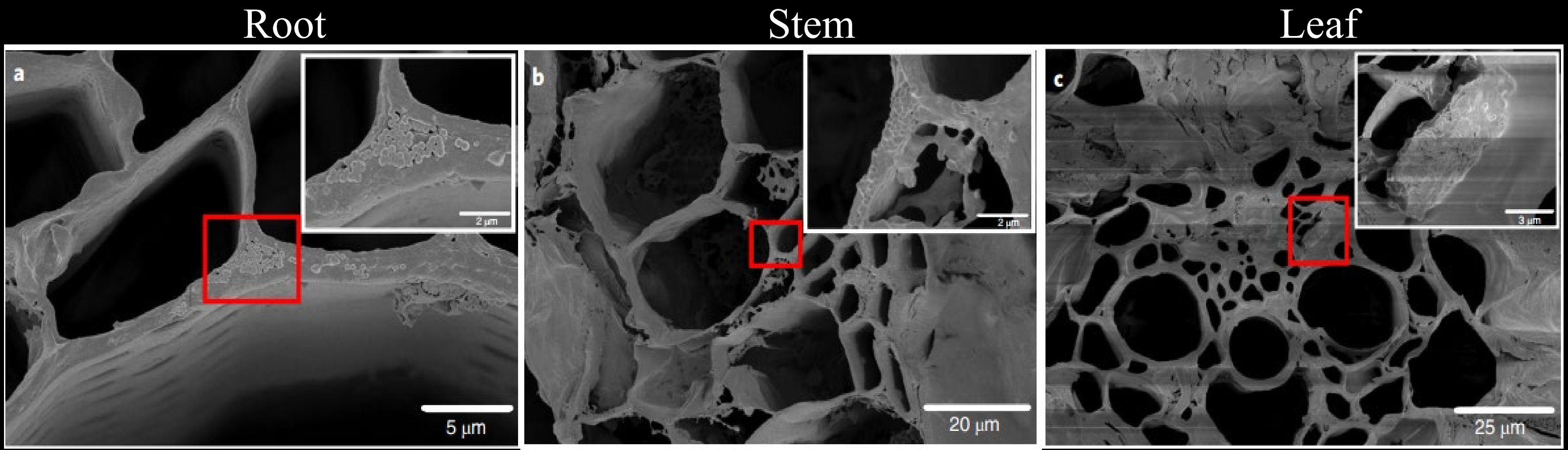
Arabidopsis thaliana



- Both positively and negatively charged nanoplastics can accumulate in *Arabidopsis thaliana*
- PS-COOH could be transported to the apoplast and xylem via the apoplastic pathway
- PS-NH_2 mainly accumulated on the root epidermis and root hairs, due to the aggregation induced by the medium and root exudates

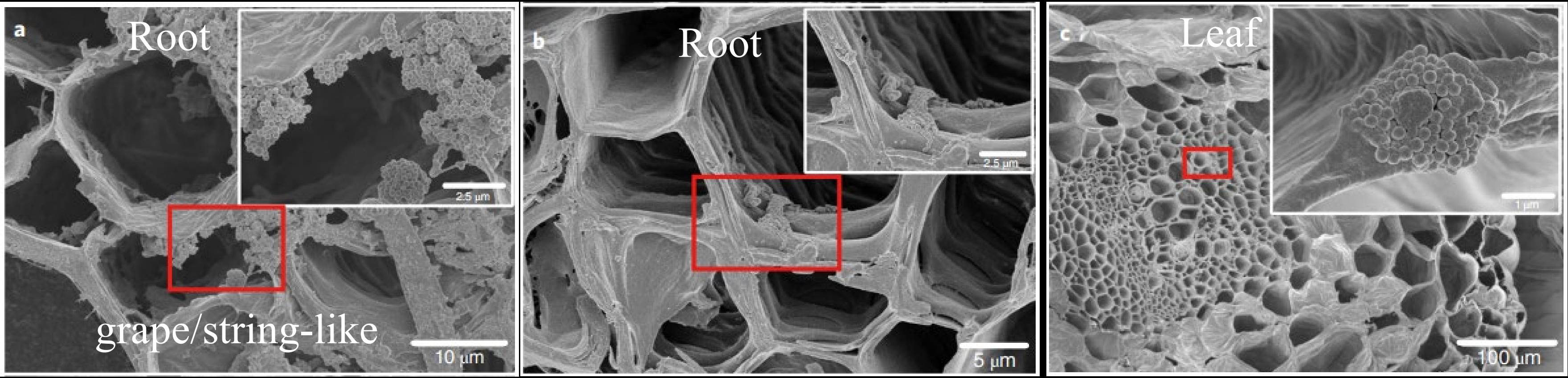
Uptake of microplastics in the terrestrial plants

Uptake of microplastics by crop plants



Triticum aestivum

SEM images of PS localization in the root, stem and leaf of a wheat plant



Lactuca sativa

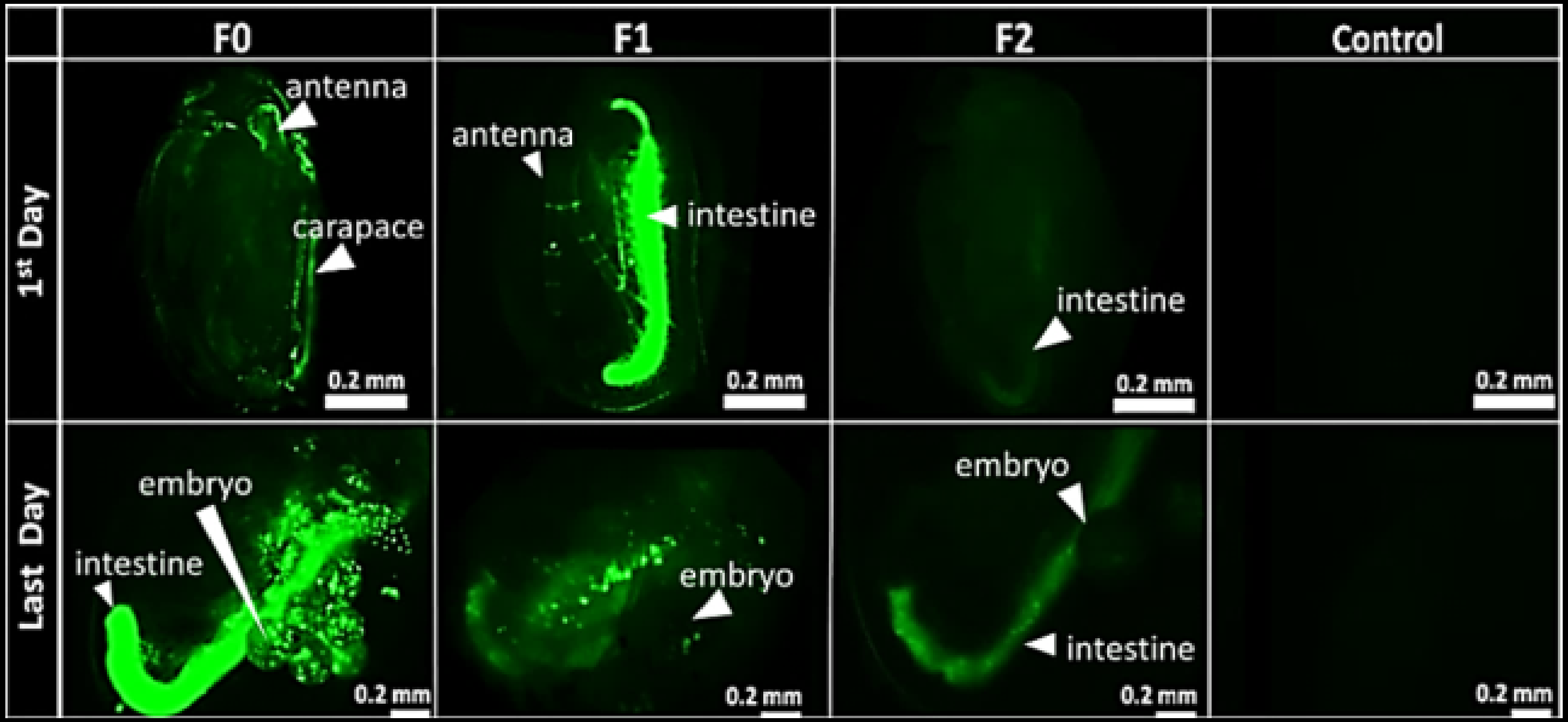
Li et al., Nat. Sustain., 2020

SEM images of PS localization in the root and leaf of a lettuce plant

- PS microplastics were observed in the roots, shoots and leaves of wheat and lettuce
- PS microplastics passed through the intercellular space via the apoplastic transport system

Uptake of microplastics in the freshwater organisms

Transgenerational effects of PS nanoplastics on *D. magna*



Daphnia magna

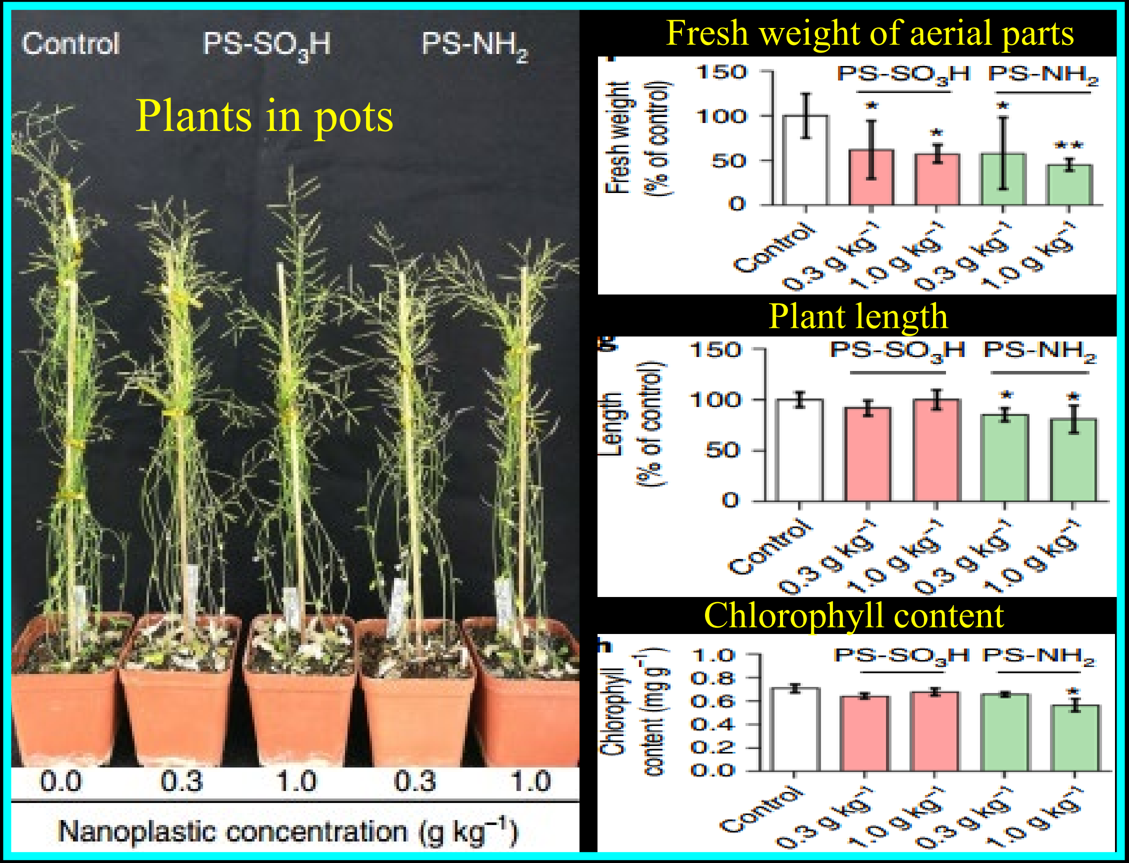
PS (20 nm) with green fluorescence

Xu et al., Environ. Sci. Technol., 2020

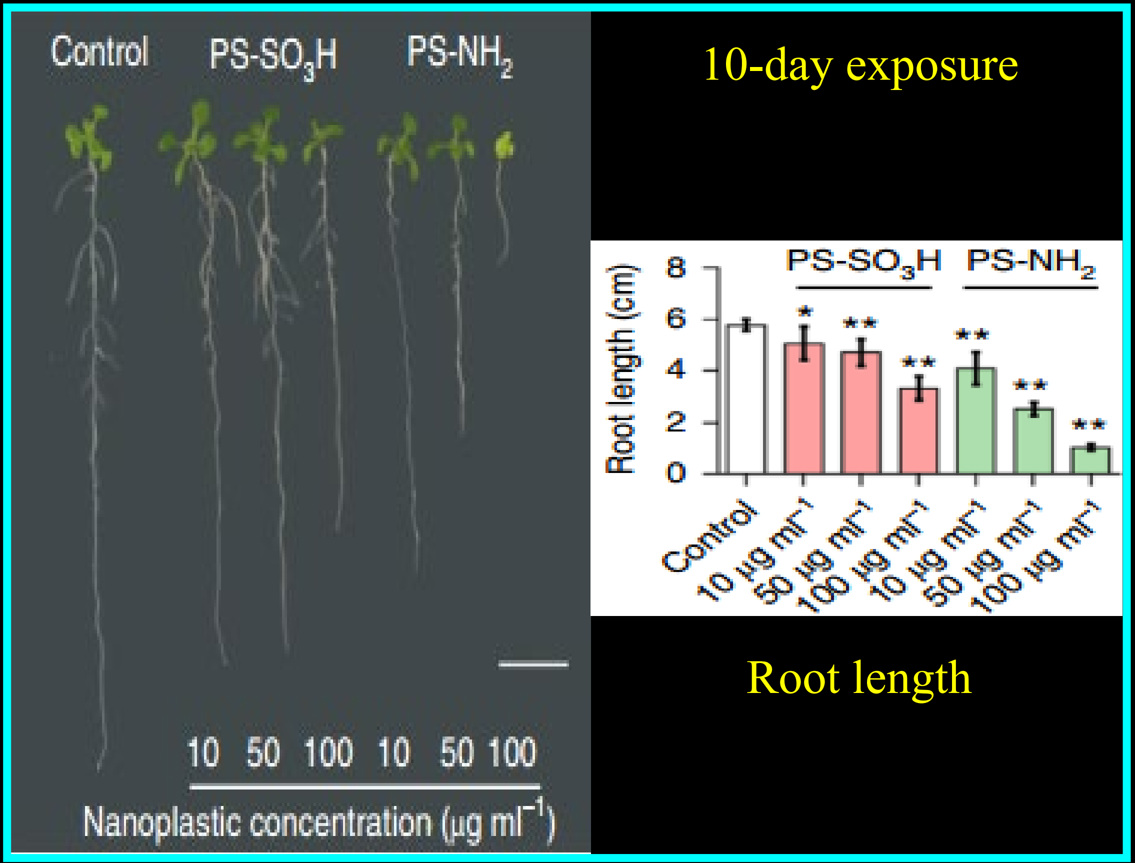
- PS nanoplastics were distributed in the intestine and brood chamber, and transferred from parent to neonates in the second and third generation
- There are two possible routes (not confirmed): Permeate into yolk granules/lipid droplets, and/or uptake via brood-chamber

Toxicity of microplastics to the terrestrial organisms

Toxicity of PS nanoplastics to *Arabidopsis thaliana*



7-week exposure



Sun et al., Nat. Nanotechnol., 2020

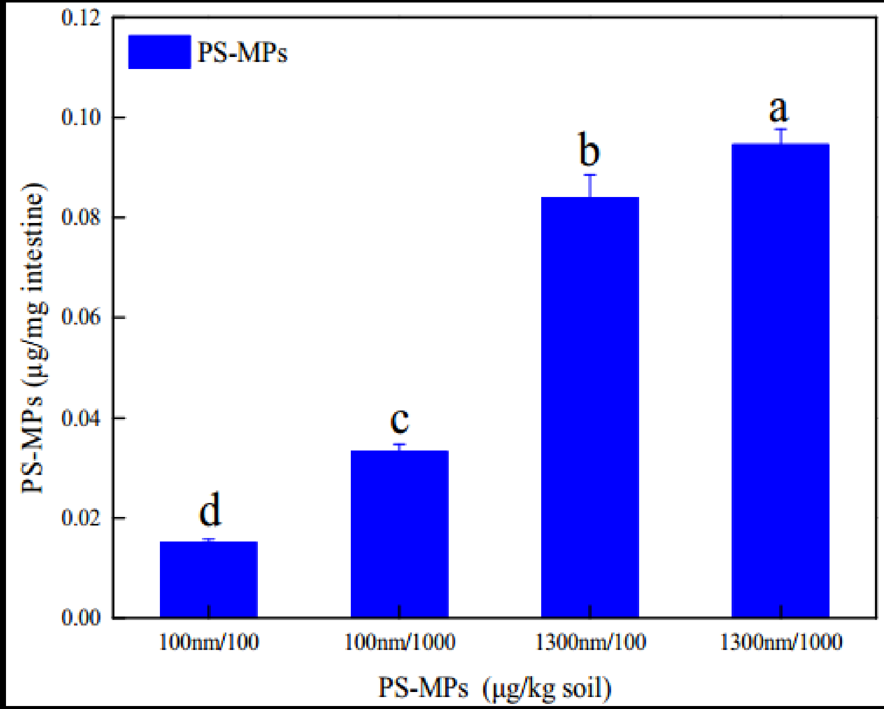
- Toxicity of $PS\text{-}NH_2$ was stronger than $PS\text{-}SO_3H$, because $PS\text{-}NH_2$ induced stronger reactive oxygen species accumulation

Toxicity of microplastics to the terrestrial organisms

Eisenia fetida

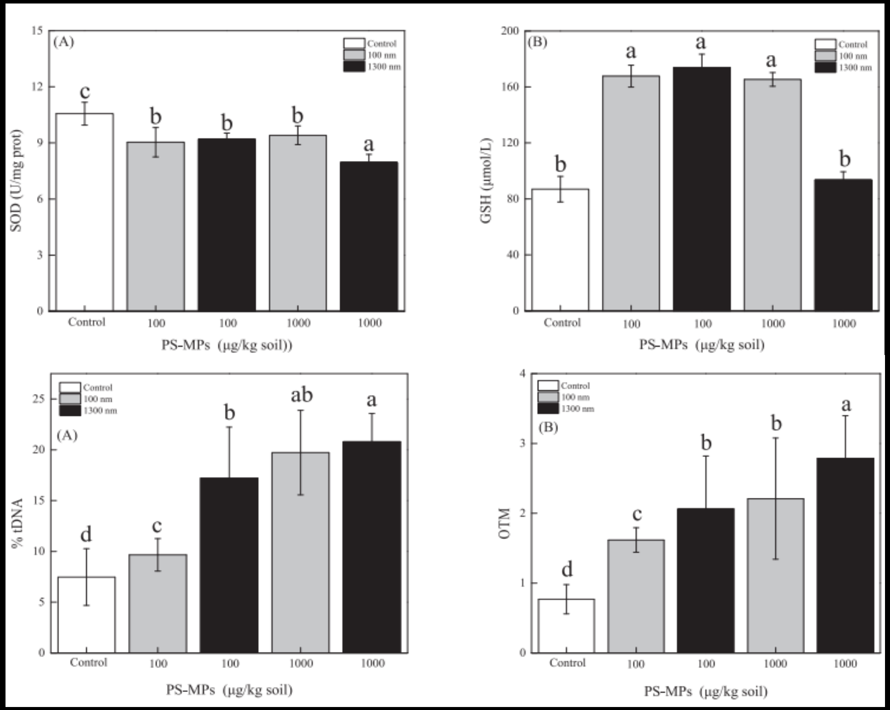
Toxicity of PS microplastics to earthworm

Contents of PS in earthworm intestines



Superoxide dismutase

Glutathione



Enzymatic activities

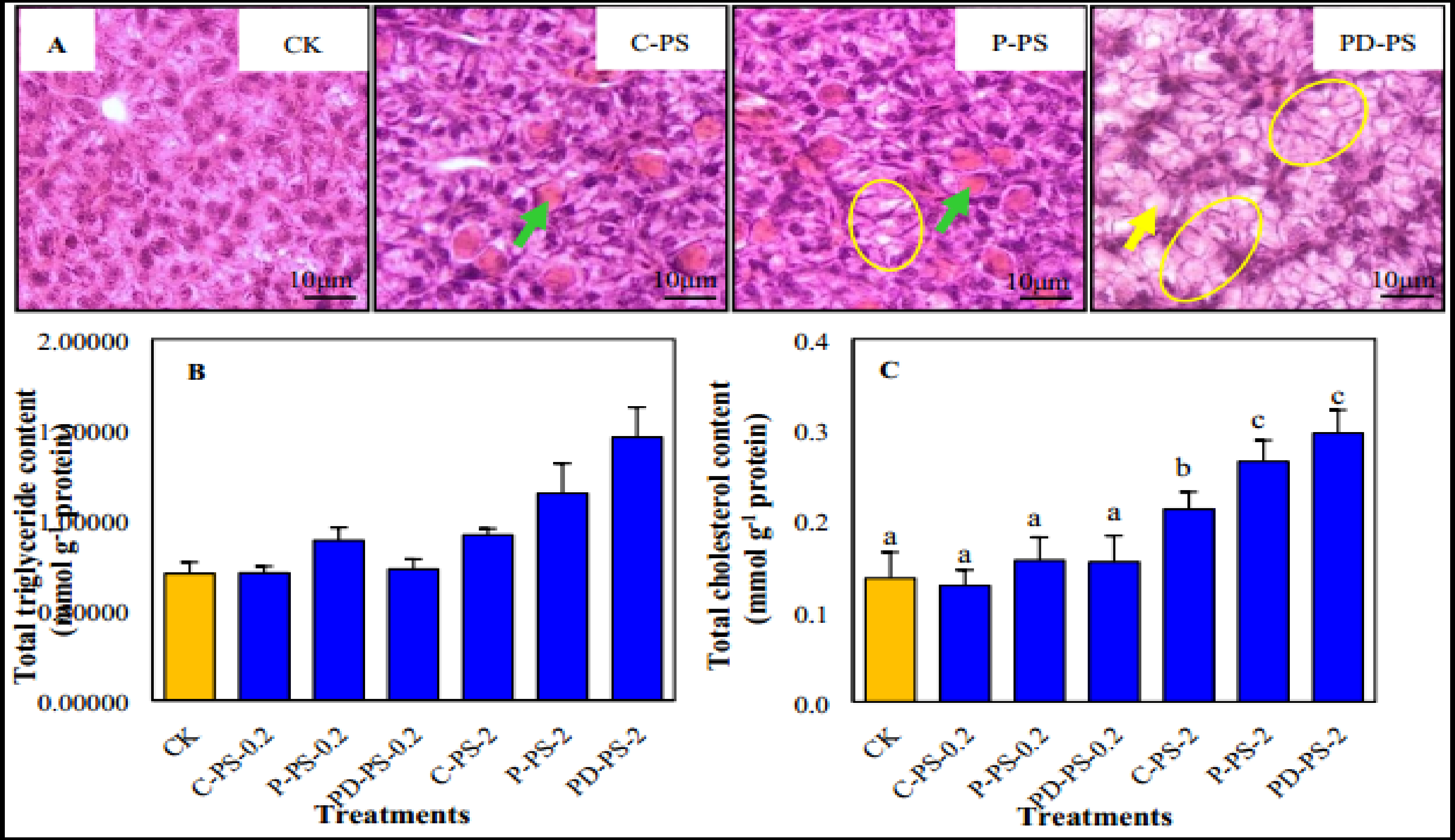
DNA damage

Jiang et al., Environ. Pollut., 2020

- PS microplastics could accumulate in the earthworm intestines
- Oxidative stress and DNA damage were induced after PS microplastics exposure
- PS (1300 nm) showed stronger toxicity to earthworms than PS (100 nm) , but the mechanism was unknown

Toxicity of microplastics to marine organisms

Toxicity of microplastics to Grouper (*Epinephelus moara*)



Epinephelus moara

Eosinophil infiltration

focal necrosis

hydropic degeneration

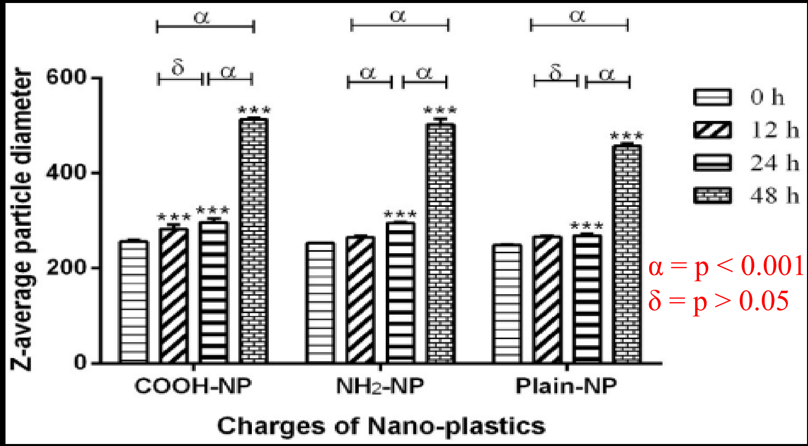
PD-PS (photodegraded PS)
> P-PS (pristine PS)
> C-PS (commercial PS)

Wang et al., Environ. Sci. Technol., 2020

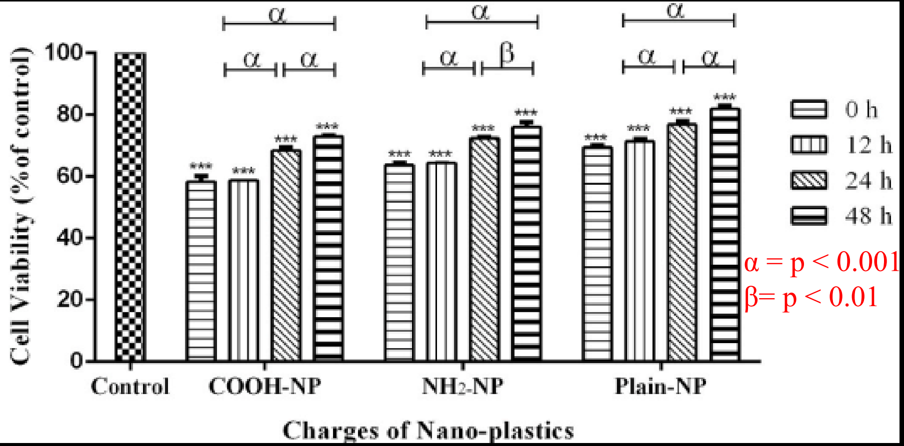
- Microplastics induced growth inhibition and hepatic/pathological damage of grouper
- The enhanced lipid deposition was one of the reasons for the aggravated hepatic lesion upon PD-PS exposure

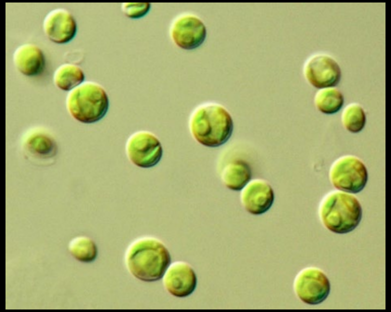
Effect of eco-corona on PS nanoplastics toxicity towards marine microalgae

PS size after incubation for EPS (extract from algae)



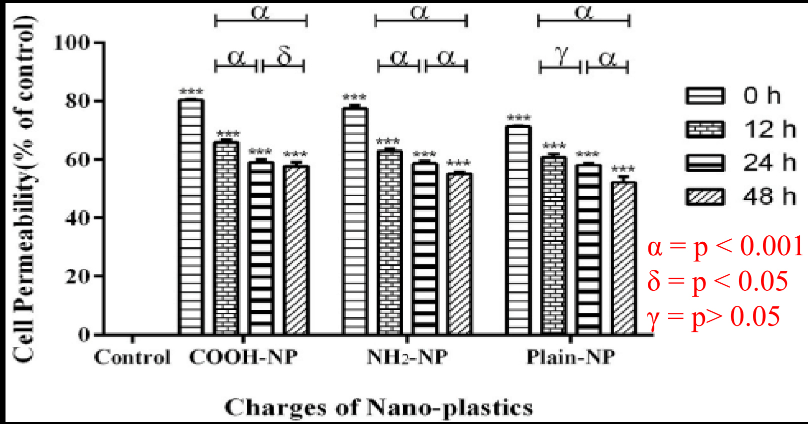
Cell viability



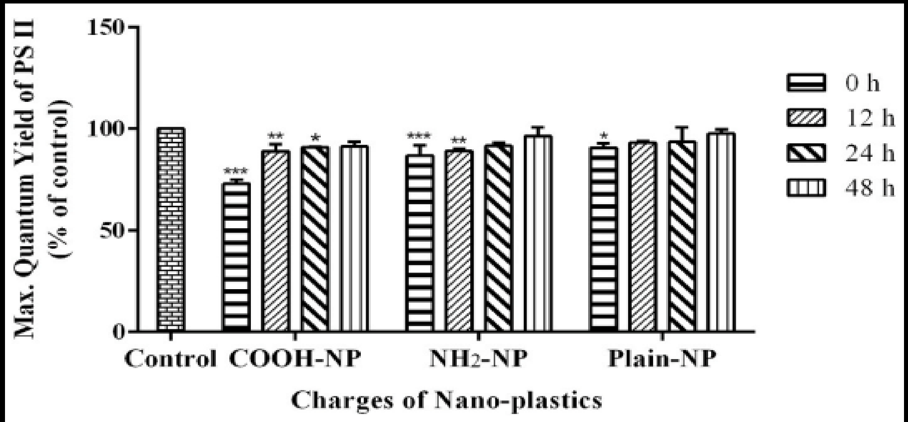


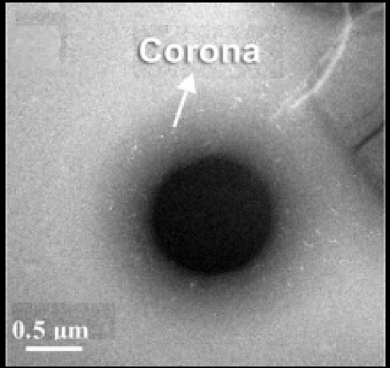
Chlorella sp

Cell permeability



Quantum yield of plasma sheath II





Dong et al., Water Res., 2020

Note: '*' indicates the difference in percentage noted with respect to control

Natarajan et al., Environ. Res., 2020

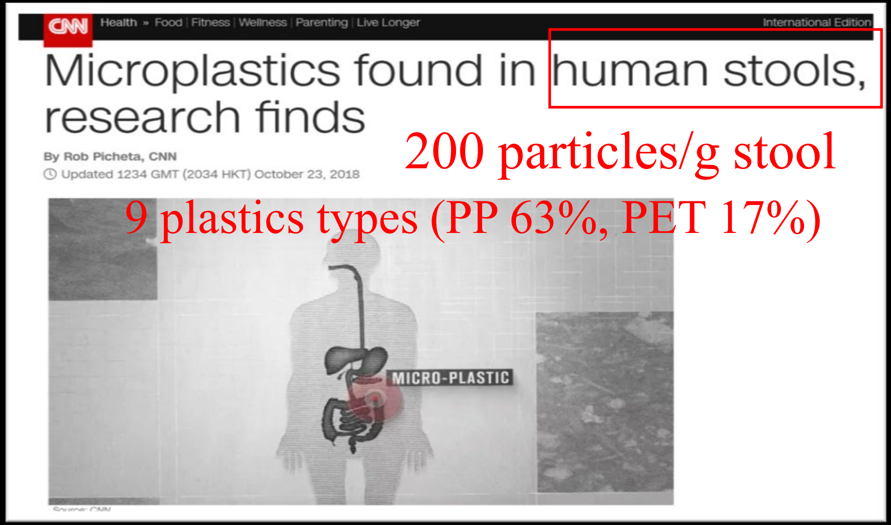
- Eco-corona formed on PS lessened the toxicity of PS nanoplastics towards algae by preventing direct contact between PS and algae
- Negatively charged PS lessened the toxicity more obviously, due to the higher binding affinity for EPS

V. Potential risk of microplastics to human health

WWF, 2019

Microplastics in seafood (0-10.5 particles/g)

Danopoulos et al., Environ. Health. Persp., 2020


CNN Health » Food | Fitness | Wellness | Parenting | Live Longer International Edition

Microplastics found in human stools, research finds

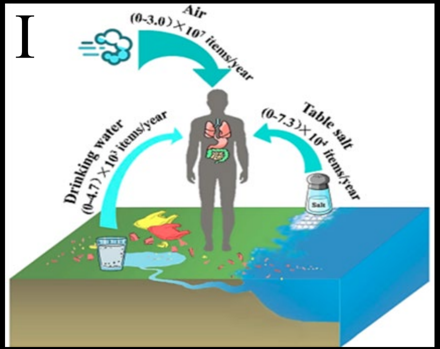
By Rob Picheta, CNN
Updated 1234 GMT (2034 HKT) October 23, 2018

200 particles/g stool
9 plastics types (PP 63%, PET 17%)

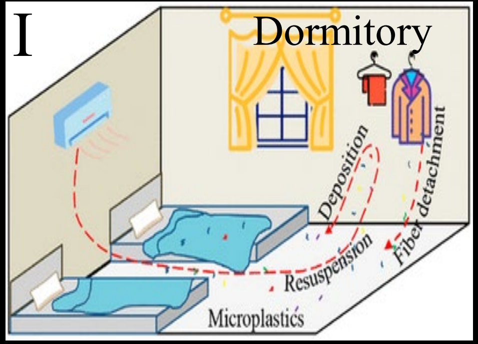
CNN, 2018; Schwabl et al., Ann Intern Med. 2019

- Microplastics could enter the human body

Major pathways of human exposure to microplastics



$0\text{-}3.0\times10^{7}$ particles/L



9.9×10^{3} particles/m²/d

1.62×10^{7} particles/L

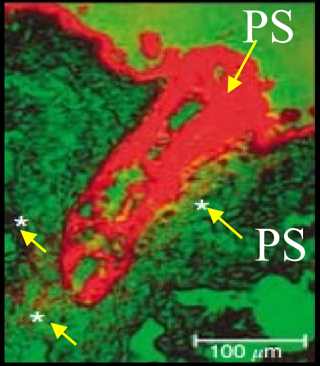
$(102\pm21.1)\times10^{6}$ particles/L

11.6 billion microplastics
3.1 billion nanoplastics

118±88 particles/L

0-10.5 particles/g

III



Nanoplastics in human skin epidermal cells (LSCM image)

I: Lung; II: Gastrointestinal; III: Skin

Lehner et al., Environ. Sci. Technol., 2019
Zhang et al., Environ. Sci. Technol., 2020
Danopoulos et al., Environ. Health. Persp., 2020
Schymanski et al., Water Res., 2018
Hernandez et al., Environ. Sci. Technol., 2019
Li et al., Nature Food, 2020
Zhang et al., Environ. Sci. Technol., 2020
Vogt et al., J. Invest. Dermatol., 2006
Ranjan et al., J. Hazar. Mater., 2021

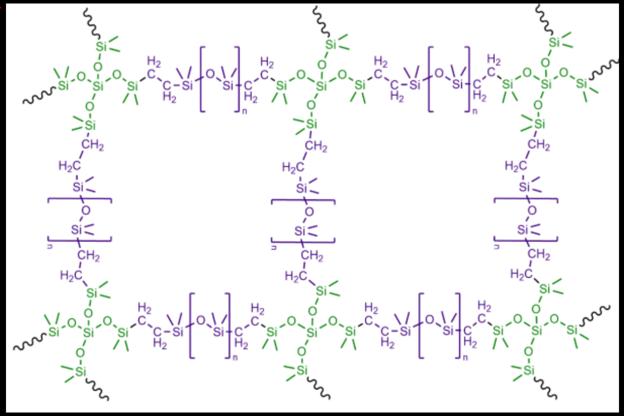
- Microplastics can enter the human body through ingestion and inhalation easily in daily life

Release of micro(nano)plastics from plastic infant feeding bottles

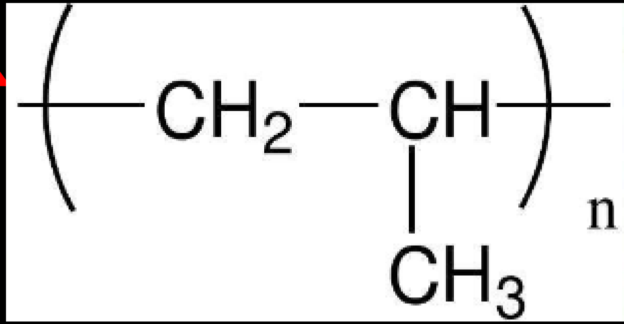
Plastic feeding bottles

Li et al., Nature Food, 2020
Su et al., Nat. Nanotechnol., 2022

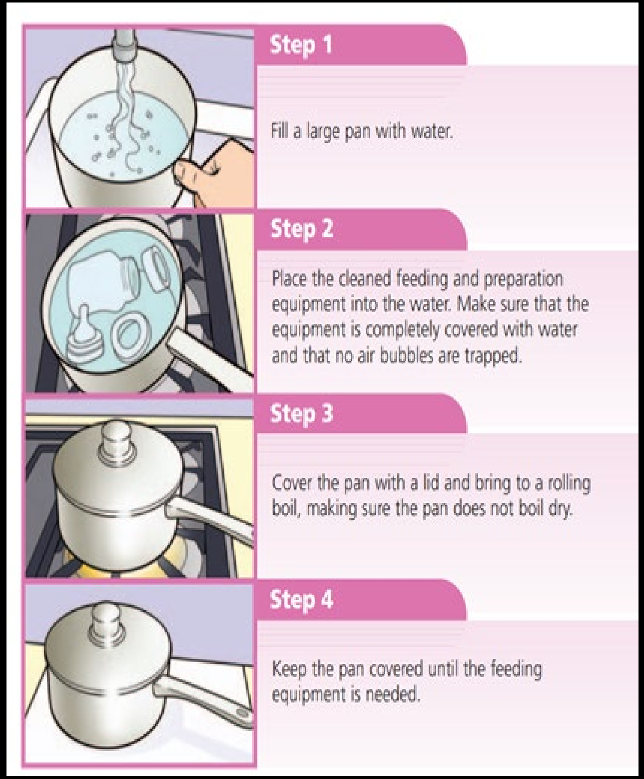
Polydimethylsiloxane (PDMS)



PP



Sterilizing

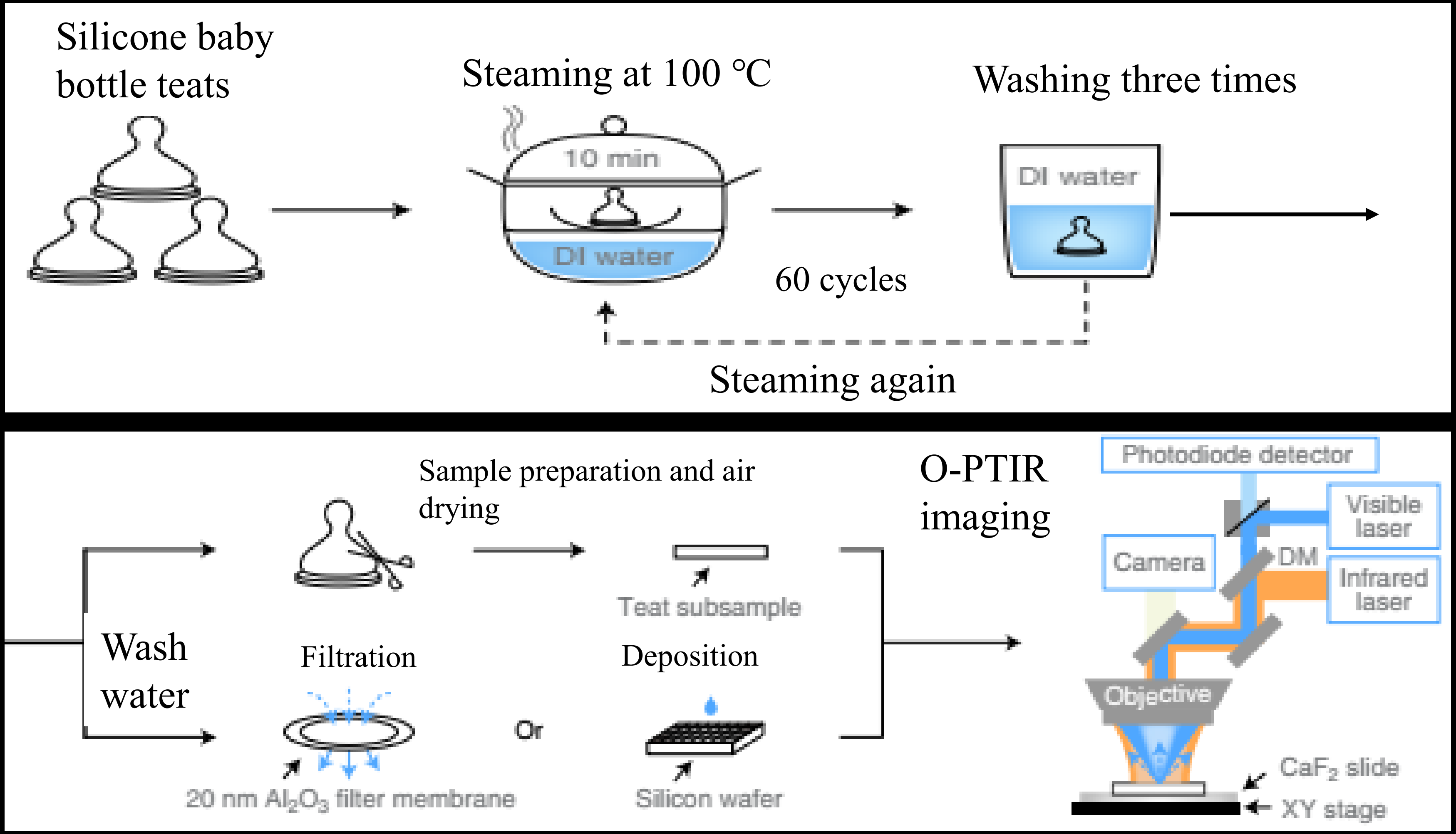


World Health Organization, 2007

Micro(nano) plastics?

- Can micro(nano)plastics be released from plastic infant feeding bottles?

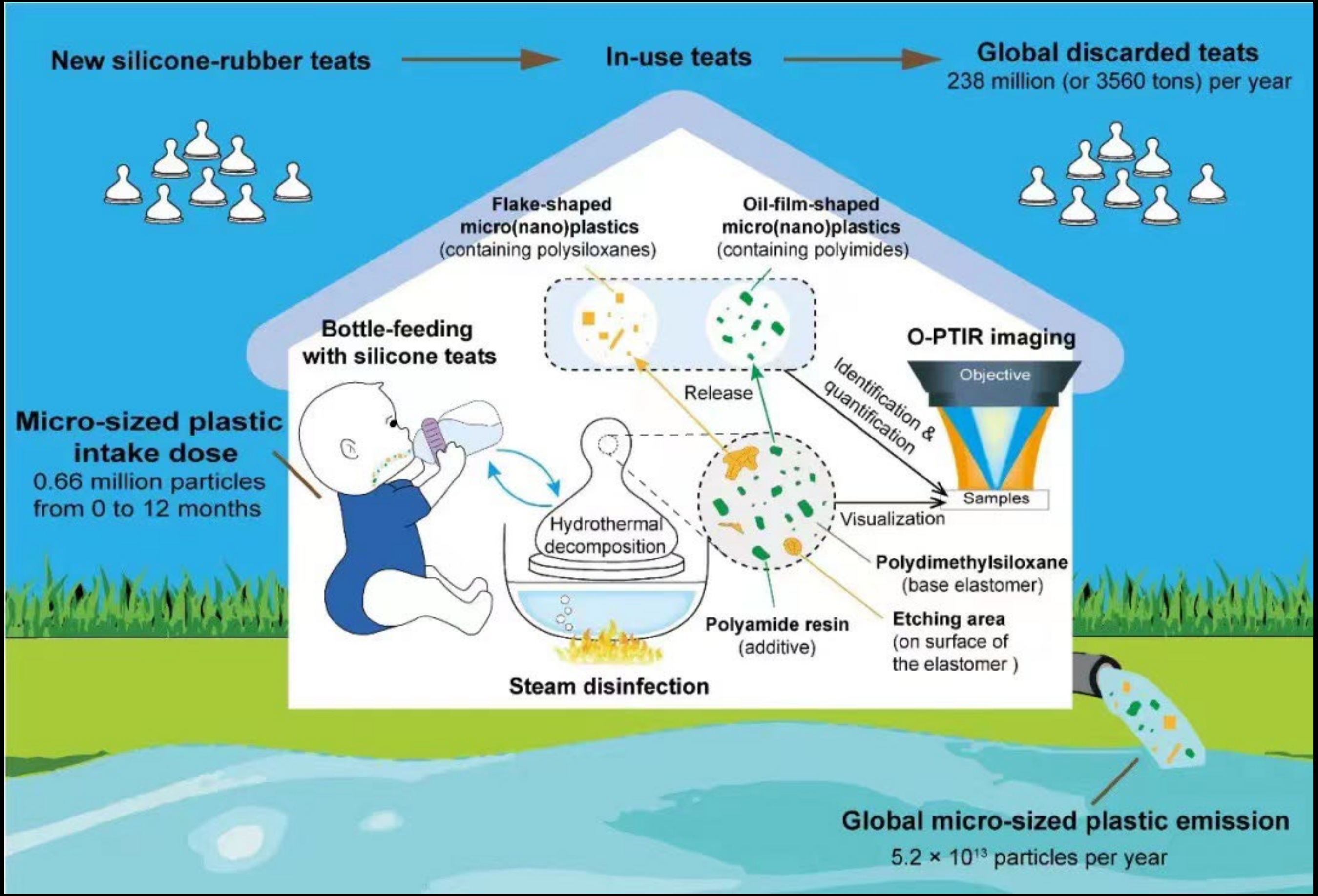
Micro(nano)plastics release from silicone-rubber baby teats



Su et al., Nat. Nanotechnol., 2022

Teat and micro(nano)plastic sample preparation

Micro(nano)plastics release from silicone-rubber baby teats

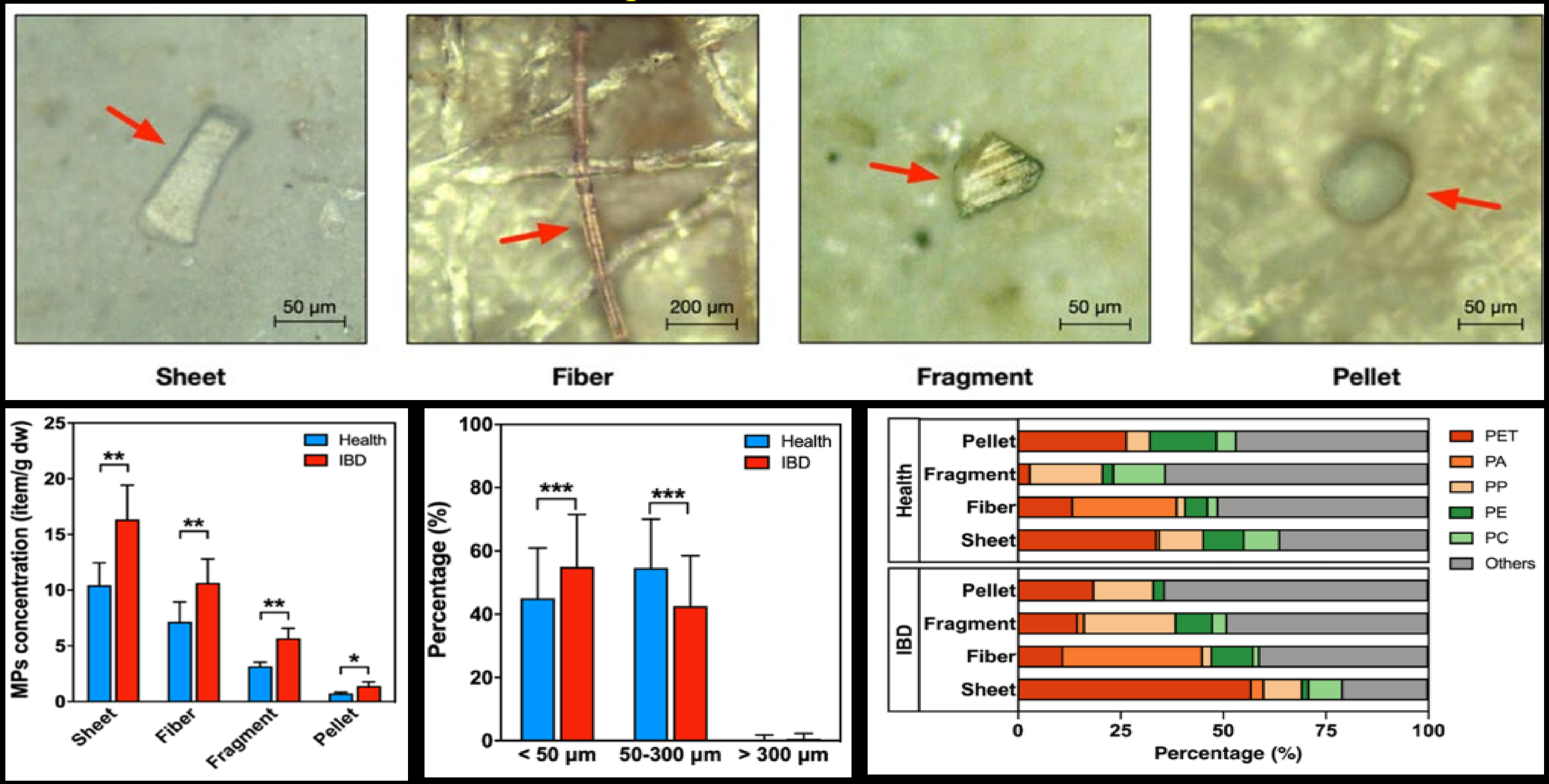


Su et al., Nat. Nanotechnol., 2022

- Flake- or oil-film-shaped micro(nano)plastics (0.6–332 μm) were generated by the steam-induced degradation of baby teats
- By the age of one year, a baby could ingest >0.66 million elastomer-derived microplastics
- Global microplastics emission from teats sterilization may be as high as 5.2×10^{13} particles/year
- The health and environmental risks of the particles are yet unknown

Microplastics and inflammatory bowel disease

Microplastics in human stools

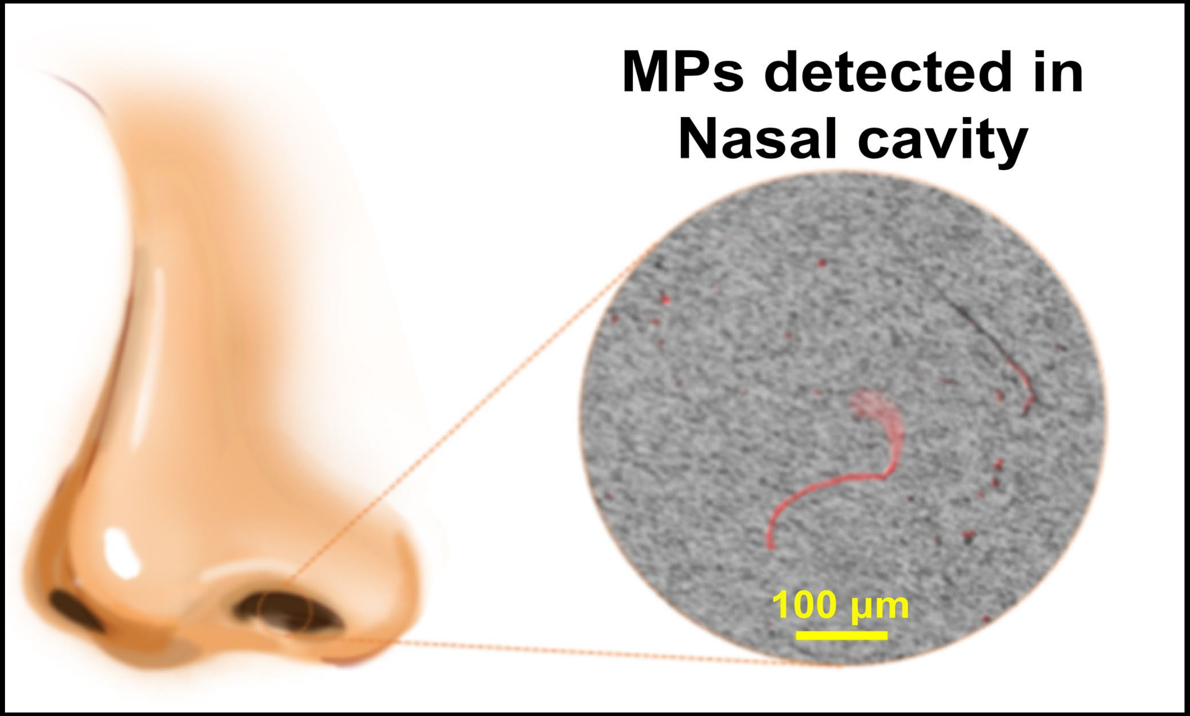


Yan et al., Environ. Sci. Technol. 2022

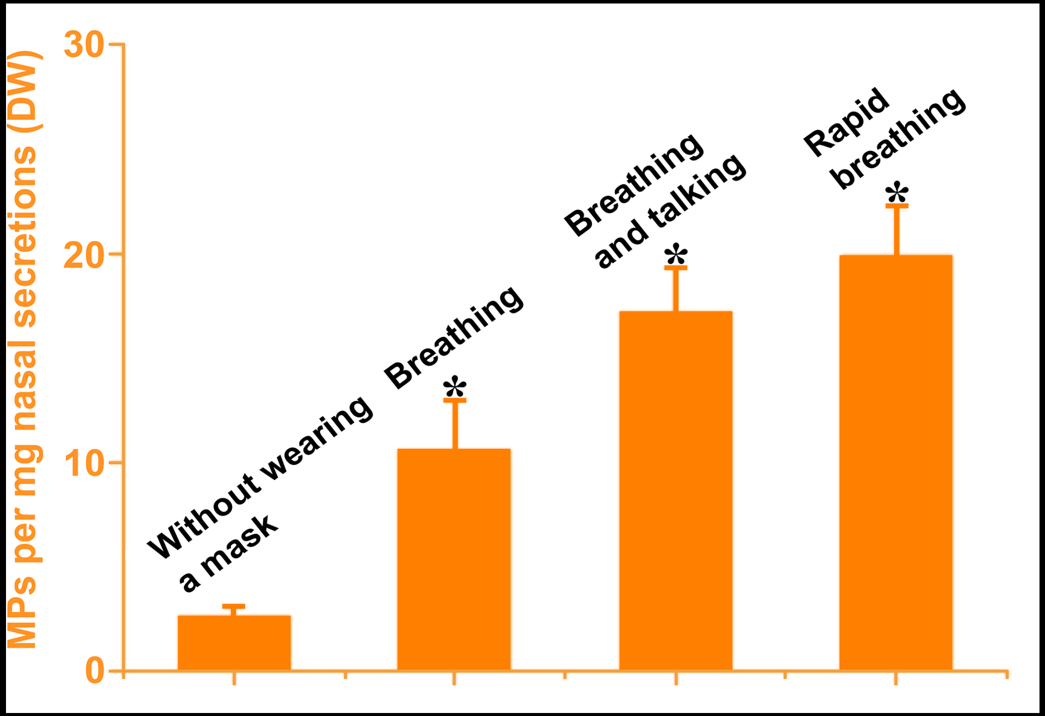
- In both healthy and inflammatory bowel disease (IBD) human stools, most microplastics were < 300 μm with the shape of sheets and fibers
- There was a correlation between fecal microplastics and inflammatory bowel disease status

Microplastics detected in nasal mucus after wearing a mask

Microplastics in human nasal mucus



Number of microplastics detected in nasal mucus



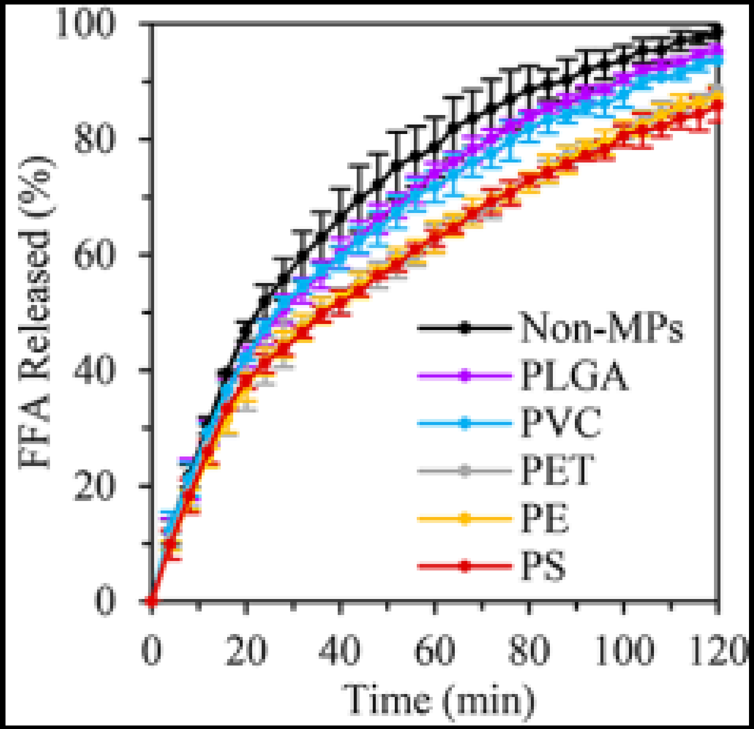
Ma et al., Environ. Pollut.,2021

- Fiber-like and spherical microplastics in the masks could be inhaled by human when wearing a mask, while the exact size and quantity are unknown
- A higher breathing frequency resulted in a larger number of microplastics detected in the nasal mucus

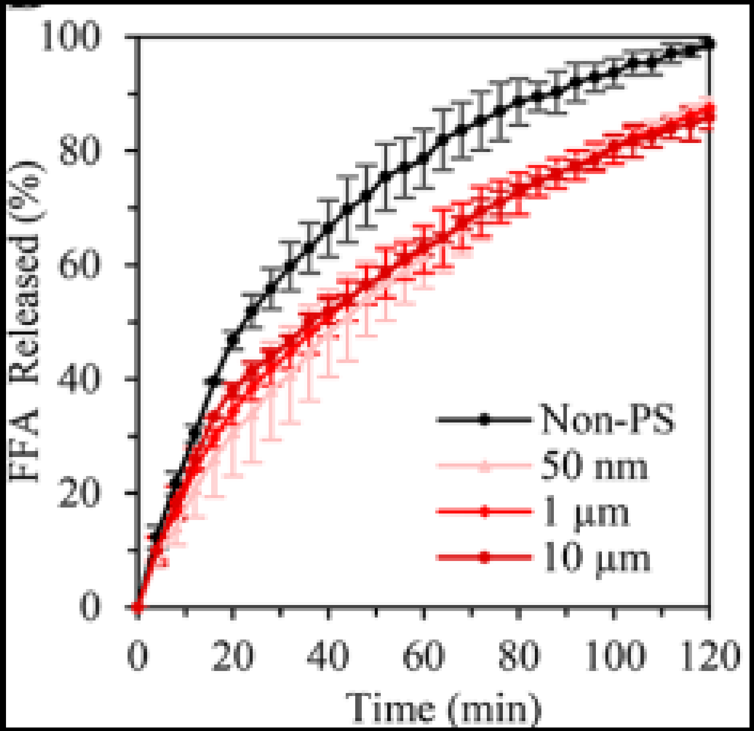
Microplastics reduce lipid digestion

Effect of microplastics on lipid digestion

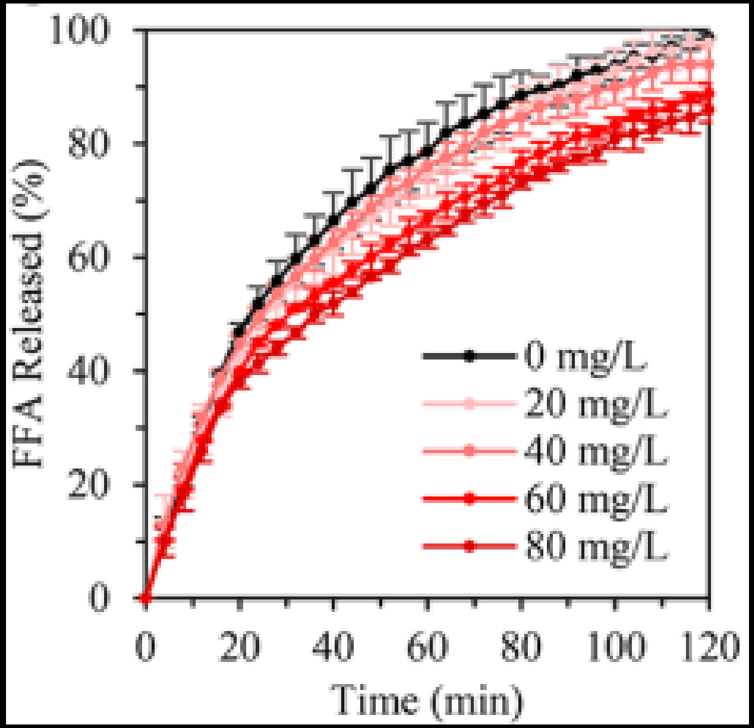
Different types



Different sizes



Different concentrations



Tan et al., Environ. Sci. Technol., 2020

- PS, PE, and PET had the strongest inhibition, much higher than PVC and poly(lactic-co-glycolic acid) (PLGA)
- Lipid digestion was highly PS concentration-dependent, while size-independent

Concluding remarks:

- Microplastics are widely distributed in seawater, soils, sediments and freshwater, even reach the most remote regions. Atmospheric transport is an important pathway for microplastics transport to remote regions.
- Adsorption, aggregation and degradation are the most important environmental processes of microplastics; degradation could regulate adsorption and aggregation behavior.
- Microplastics can be ingested by terrestrial, marine and freshwater organisms, and could become toxic by inducing oxidative stress and DNA damage; microplastics additives also increase toxicity while eco-corona/biofilm could mitigate their toxicity.
- Microplastics can enter the human body through ingestion and inhalation, possibly leading to health risks (e.g., inflammation, reduced digestion health & nutrient assimilation).

Knowledge gaps needs to be addressed in the future

- Nanoplastics should be further studied (e.g., collection, detection, environmental concentration, distribution and fate) in addition to microplastics.
- *In-situ* detection and characterization of microplastics in the environment and organisms need to be developed.
- The standard approaches on microplastics research (e.g., detection, characterization, toxicity) should be established for comparisons.
- The role of eco-corona/biofilm should be better understood, including formation mechanism, and its effect on the behavior, toxicity, internalization of microplastics
- "Trojan horse" effect need to be considered on the toxicity of microplastics and co-existing contaminants to organisms and humans.
- Transport of microplastics through important tissue barriers, including skin, intestine epithelium, placenta, and blood-to-brain barriers should be better examined and understood.

Acknowledgments

<u>My research group:</u>
Students
Postdocs
Visiting scientists

<u>Collaborators:</u>
<u>Dr. Jian Zhao</u>
<u>Dr. Hao Zheng</u>
<u>Dr. Zhenyu Wang</u>

USDA-NIFA: MAS 00549