Sustainability and Chemistry
CH5106: L8

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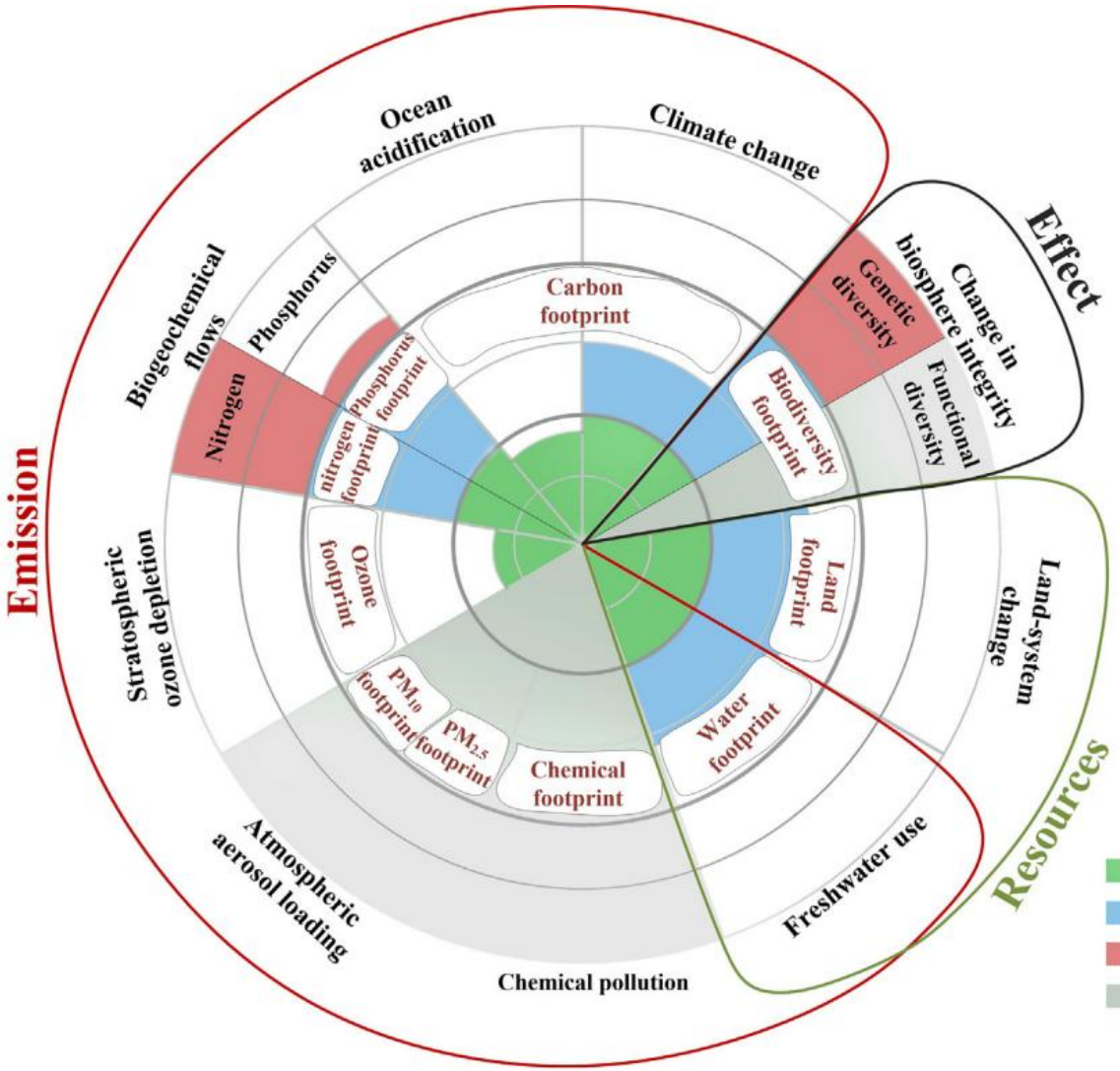
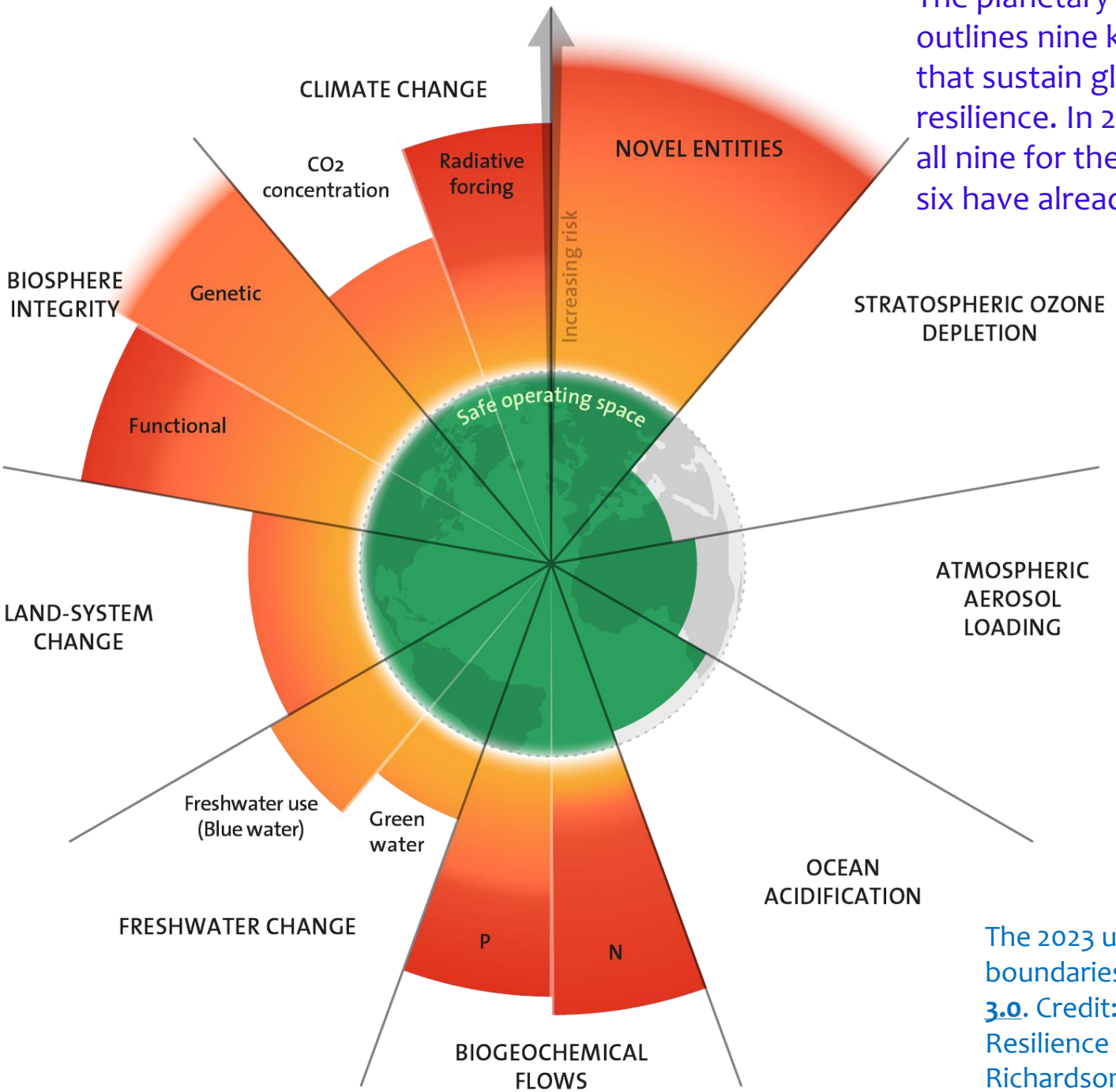


Planetary boundaries and environmental footprints (updated from Steffen et al. (2015b)): Matching environmental footprint indicators based on planetary boundaries. The outer red line circles emission footprints, green indicates resource consumption footprints, and black indicates composited footprints.
Science of the Total Environment 785 (2021) 147383

The planetary boundaries framework outlines nine key Earth system processes that sustain global stability and resilience. In 2023, scientists quantified all nine for the first time and found that six have already been transgressed.



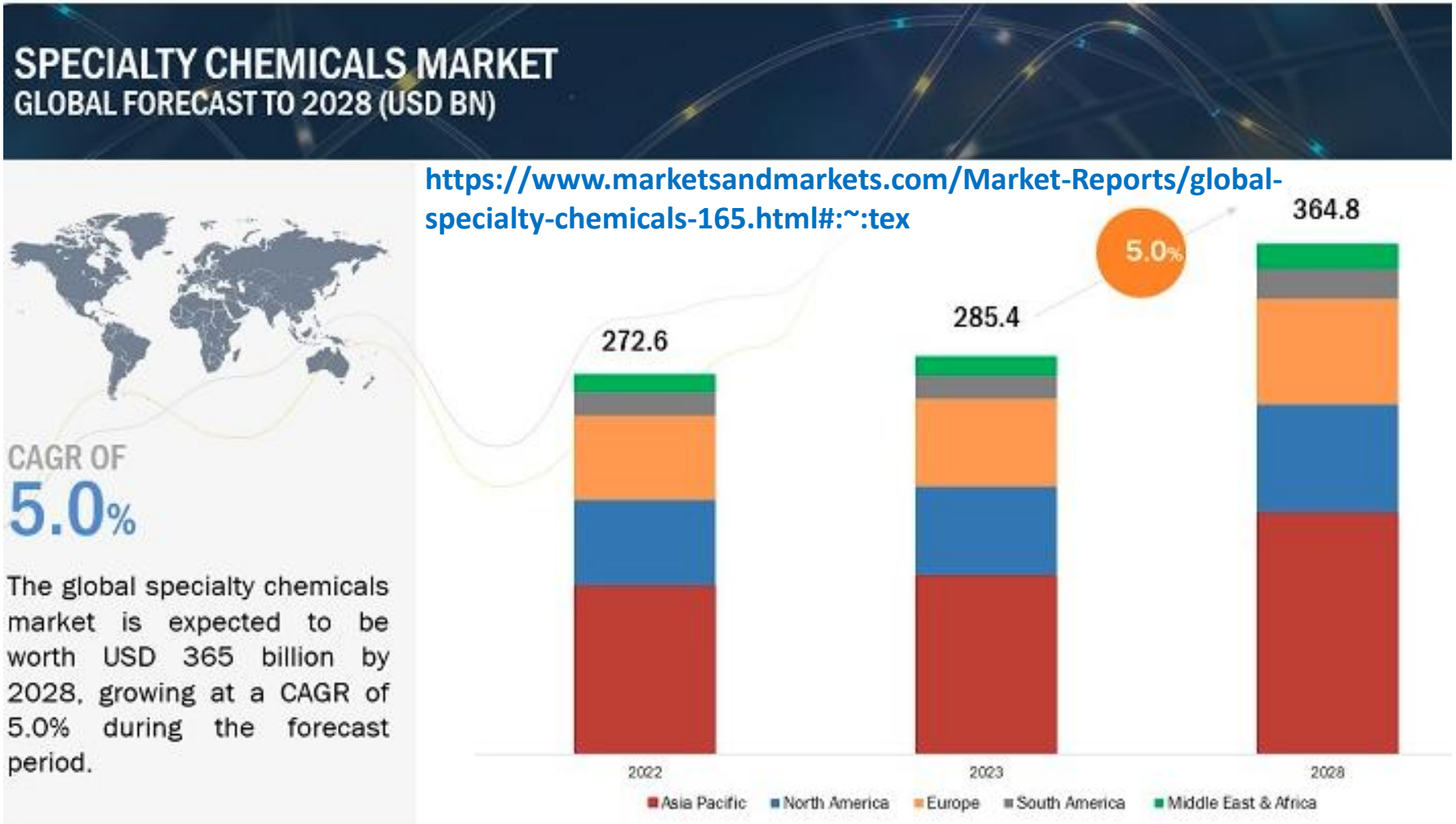
- About USD 6.2 trillion in 2024 (global chemicals market value, estimate). PR Newswire
- For context, **world chemical sales were €5.195 trillion in 2023** (latest audited global figure), implying a modest uptick into 2024. [2024 Facts and Figures - cefic]
- Longer-term signals: UNEP notes the sector could approach **~US$10 trillion by 2030** (doubling from 2017), underscoring continued growth.

Chemical Industry Outlook worth $6,324 billion by 2025 - Exclusive Report by MarketsandMarkets

The Global specialty chemicals market @ 2023: 285.4 billion

Projected market @ 2028: 364.8 billion

[5% **Compound Annual Growth Rate**]



Compound annual growth rate (CAGR)

$$CAGR = \left[\left(\frac{\text{Ending Investment Amount}}{\text{Start Amount}}\right)^{\frac{1}{\text{Number of Years}}} - 1\right]$$

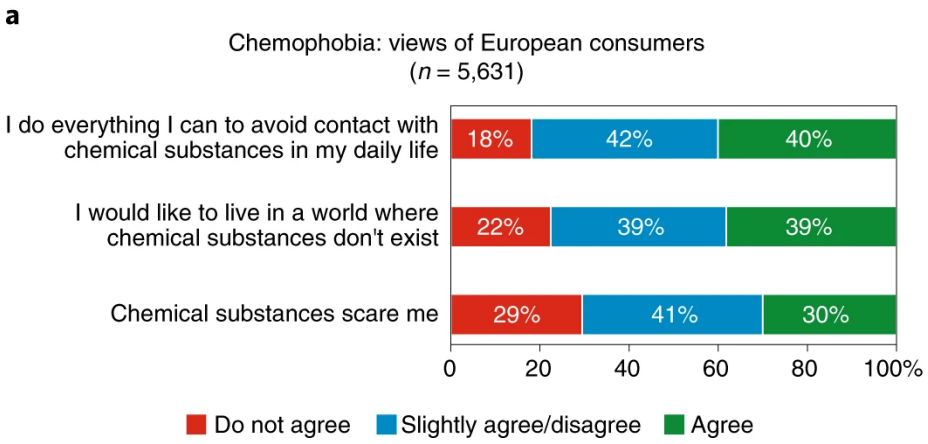
- Many chemicals once considered useful are now recognised as pollutants (Kerr 2017).
- **Organochlorine insecticides** (1950s) effectively controlled agricultural and disease-carrying pests.
- Rachel Carson's *Silent Spring* (1962) revealed their environmental persistence and cumulative risks to wildlife and humans. Despite bans, residues remain; illicit manufacture and use continue in some regions. **DDT** is a well-known example, with long-lasting global impacts.
- This reflects a repeating cycle:
  - ✓ New chemical discovery and rapid adoption, [Process/Technological interventional]
  - ✓ Delayed recognition of harmful effects, [feedback loop]
  - ✓ Subsequent bans/restrictions, [Regulatory body and policy implementation]
  - ✓ Urgent search for substitutes. [Process/Technological interventional]
  - ✓ Often, replacements bring new risks, creating repeated "pulses" of chemical release into ecosystems and food chains.
- Negative side-effects typically emerge only after widespread exposure.

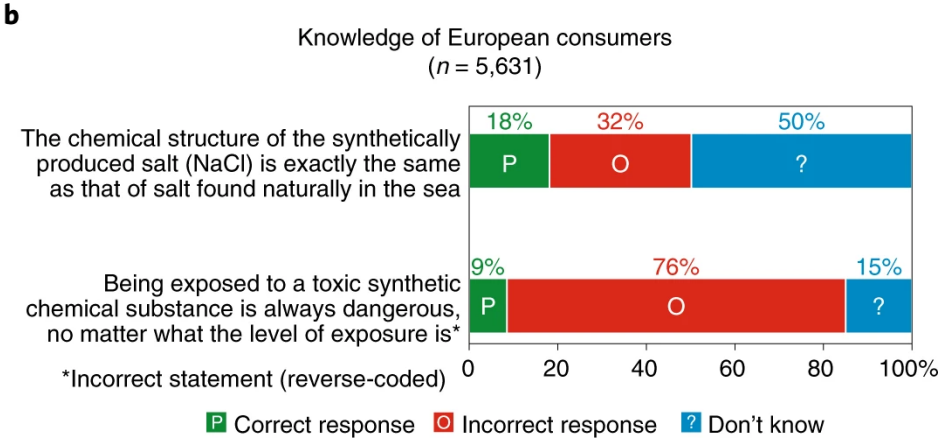
Anthropogenic chemicals are chemical substances that are produced, modified, or released into the environment as a result of human activities. Pollution is a major environmental threat, with critical risks to male fertility, cognitive health, and food security.

Fragmented knowledge, weak pollution controls, and gaps in understanding chemical exposure and mixtures leave populations vulnerable. Urgent global awareness, coordinated action, and stronger scientific scrutiny are essential to mitigate these escalating risks. [Environment International 156 (2021) 106616]

Beyond the anthropogenic dispersal of geogenic chemicals, **humans have synthesized over 140,000 novel substances—possibly exceeding 350,000** according to recent inventories. Many are toxic even at low doses, especially in mixtures or as breakdown products once released into the environment.[Environment International 156 (2021) 106616]

Surveying chemical knowledge in eight European countries

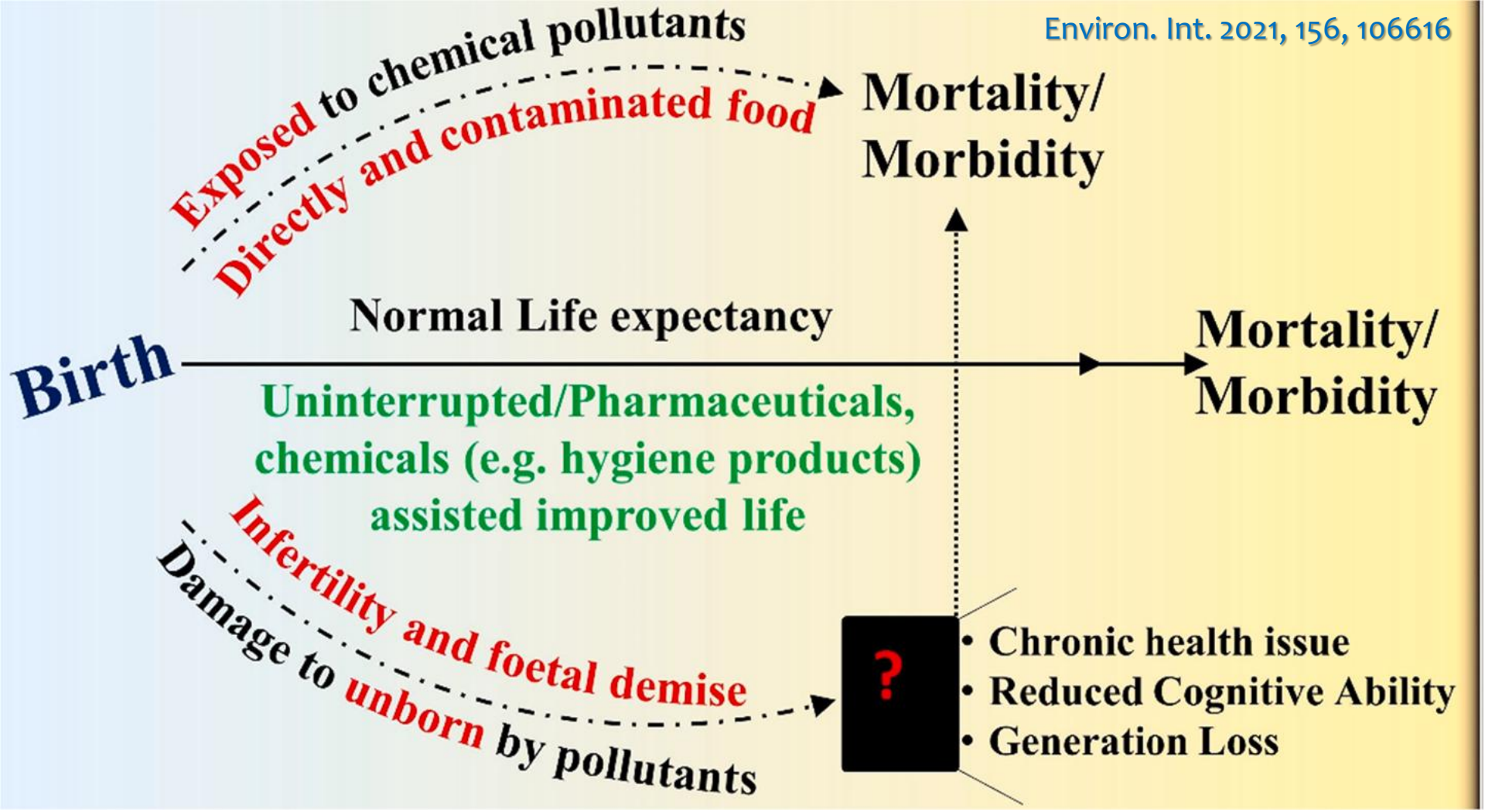




a, Responses to three questions designed to provide a measure of chemophobia. **b**, Responses to two questions designed to gauge the chemical knowledge of the consumers taking part in the survey.[**Nat. Chem. 11, 1071–1072 (2019)**]

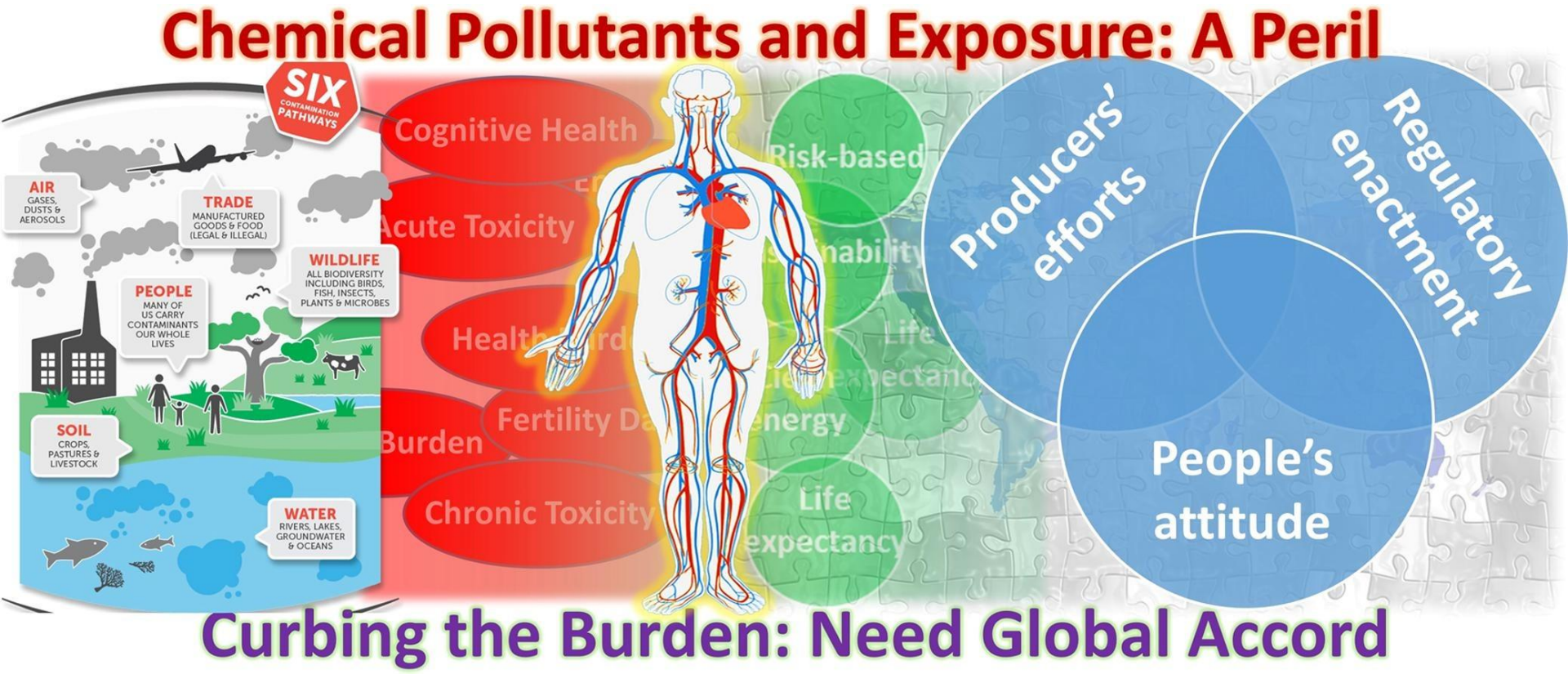
Strengthening science education and public outreach is vital to counter chemophobia, which can hinder policy and innovation. Chemists and toxicologists must stress that risk depends on dosage, not whether a chemical is natural or synthetic. A broader understanding of these principles can reduce fear and support more informed decisions.

Environ. Int. 2021, 156, 106616



This schematic recognises that normal life expectancy cannot exclude the enormous benefits of pharmaceuticals or other chemicals in the quality of human life. The length of the straight solid line represents lifespan as normal with/ without chemicals-assisted improvement; the length of the upper curved dash-dotted line represents potentially the shorter lifespans than normal; the length of the lower dash-dotted line symbolises the pollutant-impacted chronic health issue which causes significant poor quality of lifespan, while it could also lead a shorter lifespan than normal (see round dotted line).

Chemical pollution poses an escalating threat to humanity—undermining male fertility, cognitive health, and food security—yet critical knowledge gaps remain about the risks from chemical dispersal, mixtures, and recombination in the environment.



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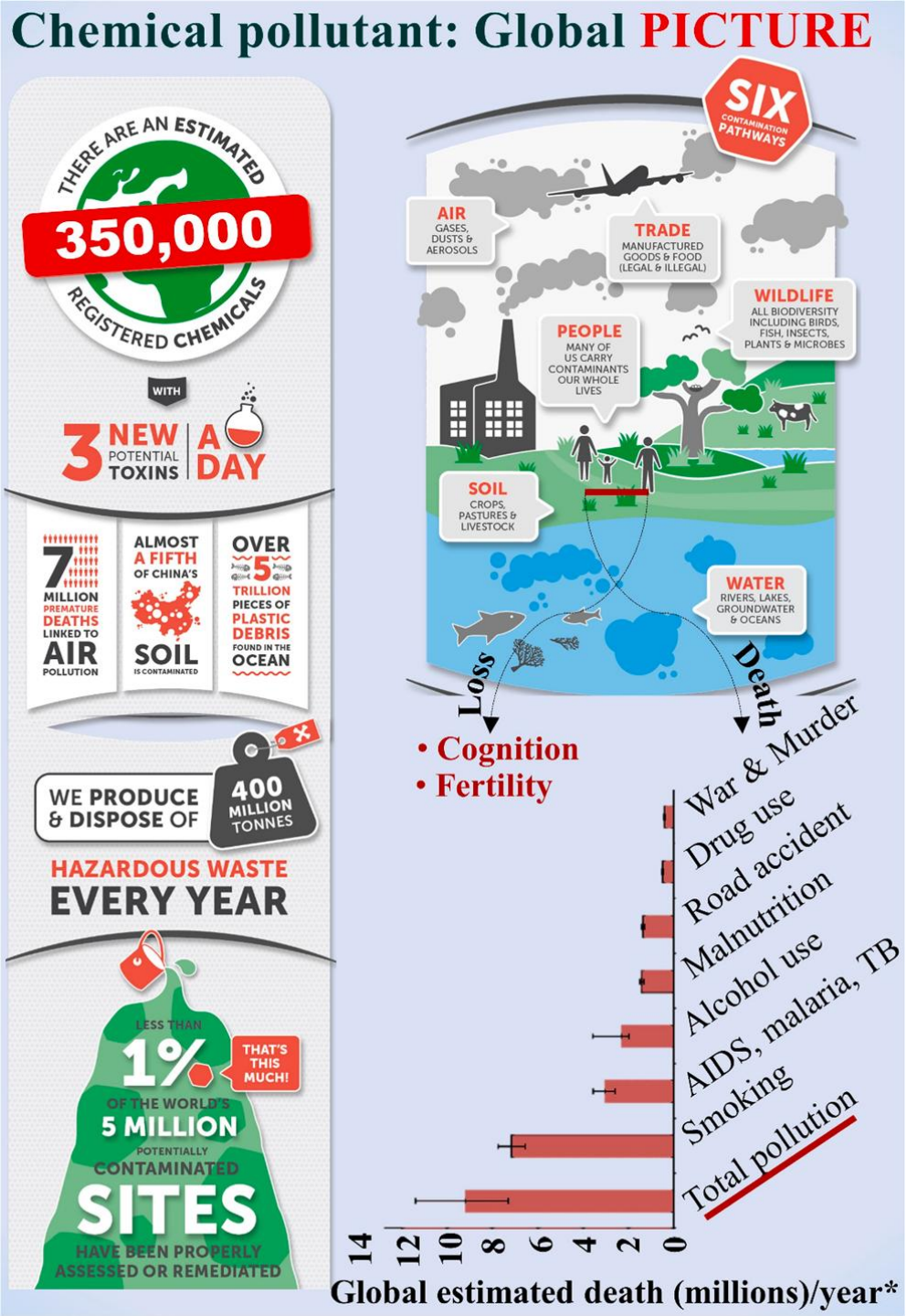
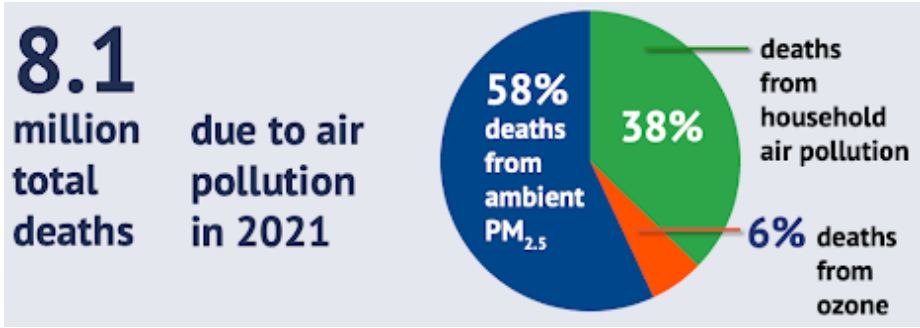


Chemical pollution moves through six major pathways—soil, air, water, wildlife, people, and trade—causing severe environmental and health impacts. Pollution-related deaths, estimated at 9–10 million annually, exceed those from any other major risk factor, far surpassing the 2 million global deaths from COVID-19 in its first year (WHO 2021).

Fig. 1. The number of "silent" deaths caused by environmental pollution exceeds any other widely recognized risk factor.



https://healthpolicy-watch.news/air-pollution-kills-a-child-every-minute/, **2024 data.**

[Environment International 156 (2021) 106616]

Chemical pollutants contribute to economic losses and health issues globally:

Economic losses:

- Contamination of food chain reduces food security and productivity of agricultural lands
- Biodiversity loss, including decline in pollinator populations, negatively impacts ecosystem services like crop pollination
- Premature deaths and disability from pollution exposure result in significant economic costs

Health issues:

- Exposure to chemicals like heavy metals, pesticides, and persistent organic pollutants can impair cognitive function, cause reproductive disorders, and increase risk of non-communicable diseases
- Prenatal exposure to pollutants can lead to developmental issues and lower IQ in children
- Pollution is estimated to cause over 9 million premature deaths per year globally

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Since 1987, WHO has periodically issued health-based air quality guidelines to assist governments and civil society to reduce human exposure to air pollution and its adverse effects. The WHO air quality guidelines were last published in 2006. Air quality guidelines – global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide (WHO Regional Office for Europe, 2006) provided health-based guideline levels for the major health-damaging air pollutants, including particulate matter (PM), ozone (O3), nitrogen dioxide (NO2) and sulfur dioxide (SO2). [(https://www.sciencedirect. com/journal/environment- international/specialissue /10MTC4W8FXJ]

PM0.1: Particles with aerodynamic diameter of ≤ 0.1 µm), PM2.5 (≤ 2.5 µm) , PM10 (≤ 10 µm)

Exceedance of the air quality guideline (AQG) levels is associated with important risks to public health. These guidelines are not legally binding standards; however, they do provide WHO Member States with an evidence-informed tool that they can use to inform legislation and policy. Ultimately, the goal of these guidelines is to guide to help reduce levels of air pollutants in order to decrease the enormous health burden resulting from exposure to air pollution worldwide. These guidelines do not include recommendations about pollutant mixtures or the combined effects of pollutant exposures.

In response to this growing awareness, the 68th World Health Assembly adopted resolution WHA68.8, Health and the environment: addressing the health impact of air pollution, which was endorsed by 194 Member States in 2015.

(WHO global air quality guidelines, 2021 [file:///C:/Users/Amitava%20Das/Downloads/9789240034433-eng.pdf; ISBN 978-92-4-003443-3]

These guidelines do not include recommendations about pollutant mixtures or the combined effects of pollutant exposures.

International regulation of toxic chemicals began with treaties such as the Vienna Convention for the Protection of the Ozone Layer (1985) and the Basel Convention on hazardous waste movements (1989). These were followed by the Stockholm Convention on Persistent Organic Pollutants (POPs, 2001) and the Minamata Convention on Mercury (2013). The Stockholm Convention, in force since 2004, remains the most comprehensive global mechanism for POPs control. Yet its progress has been limited: only 26 of an estimated 350,000 synthetic chemicals (< 0.01%) have been banned, with nine additional substances under review in Annexes B and C.
[http://www.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx (access: 05 February, 2021)]

[Environment International 156 (2021) 106616]

Pollution impacts on cognitive health:

Recent studies have revealed significant impacts of various industrial pollutants on the human brain and central nervous system. Fine particles, designated PM10, PM2.5, or ultrafine PM0.1, which commonly arise from industrial waste, ash and the combustion products of fossil fuel, can migrate into the brain through the olfactory bulb, the neural structure responsible for the sense of smell. Ultrafine particles also produce cytokines that inflame the lungs or the nasal epithelium and further attack brain cells.

Pollution impacts on cognitive health

- Recent studies show significant impacts of industrial pollutants on the human brain and central nervous system (Underwood, 2017).
- Fine particles (PM10, PM2.5, PM0.1) from industrial waste, ash, and fossil fuel combustion can enter the brain via the olfactory bulb.
- Ultrafine particles trigger cytokine production, inflaming the lungs or nasal epithelium and damaging brain cells (Underwood, 2017).
- Seaton et al. (2020) proposed that particle exposure to brain blood vessels may cause inflammation and microhaemorrhages in the blood–brain barrier wall.
- Roberts et al. (2013) linked hazardous air pollutant exposure at birth with autism spectrum disorder (ASD) in the Nurses' Health Study II cohort (325 cases, 22,101 controls).
- Elevated perinatal exposures to diesel, lead (Pb), manganese (Mn), and cadmium (Cd) were significantly associated with ASD incidence.
- Children of mothers exposed to air pollution during pregnancy showed a doubled incidence rate of ASD.
- In Canada, residents living within 50 m of major roads had higher dementia risk from exposure to PM2.5, PM10, and NO_2 compared with those >150 m away (Chen et al., 2017b).
- Lead from urban roadways has been linked to reduced cerebral ability (Laidlaw et al., 2017).

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- A 20-year meta-study in China found that children exposed to **fluoride**-contaminated drinking water had a fivefold higher incidence of impaired cognitive performance compared to unexposed children (Tang et al., 2008).
- In vivo studies indicate that per- and poly-fluoroalkyl substances (**PFAS**) are potentially neurotoxic to human neuroblastoma cells. PFAS exposure can alter methylation regulation in brain-derived neurotrophic factor, potentially contributing to behavioural problems (Guo et al., 2017).

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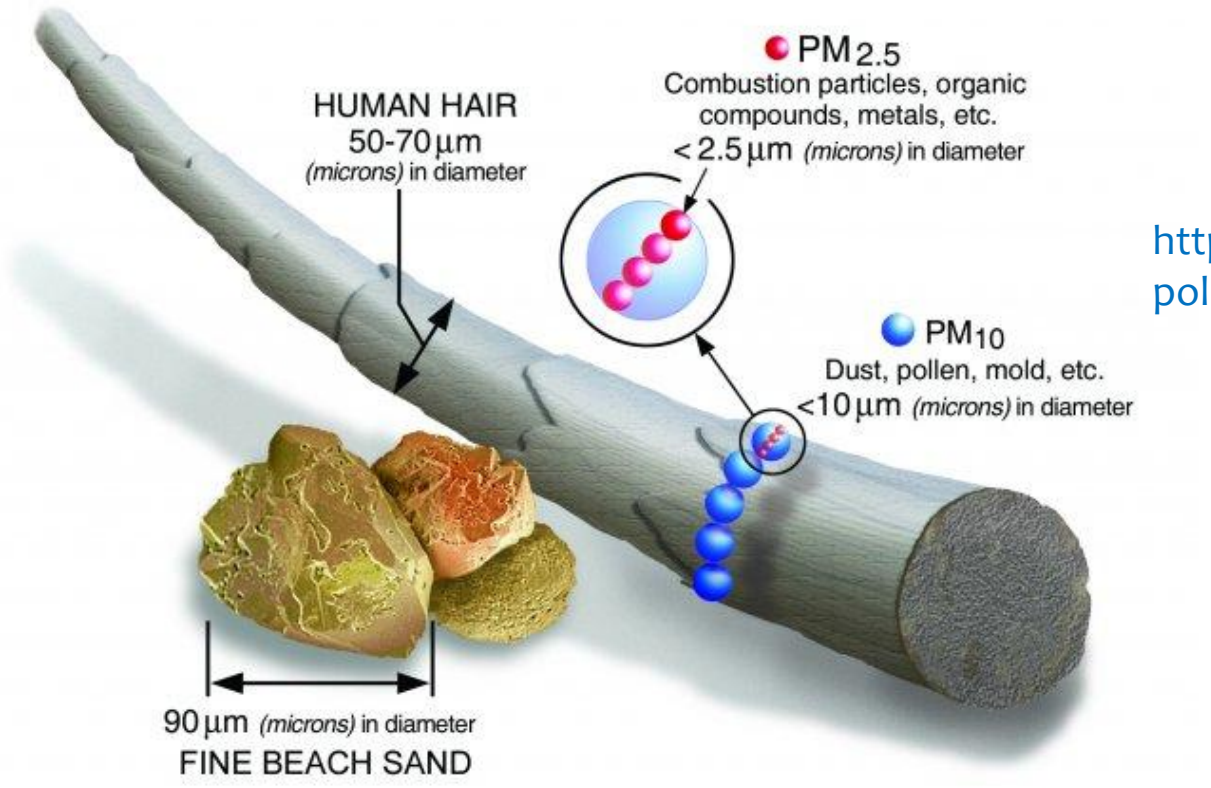
PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air.

Particle pollution includes:

$PM_{0.1}$: inhalable particles, with diameters that are generally ≤ 0.1 μm.

PM_{10}: inhalable particles, with diameters that are generally ≤ 10 μm.

$PM_{2.5}$: fine inhalable particles, with diameters that are generally ≤ 2.5 μm.



https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

Particulate matter (PM), a major component of environmental pollution, consists of fine (PM2.5) and ultrafine (PM0.1) particles that penetrate deep into the body, causing respiratory, cardiovascular, neurological, and endocrine-related health effects.

PM2.5 and PM0.1 (ultrafine particles) are not classic endocrine-disrupting chemicals (EDCs) like bisphenol A, phthalates, or pesticides. However:

- They can **carry or adsorb EDCs** (e.g., heavy metals, PAHs, dioxins, phthalates) on their surfaces.
- Once inhaled, these particles **enter circulation**, cross biological barriers, and may **alter hormone levels** by triggering oxidative stress and inflammation.
- Studies suggest associations between **PM exposure and endocrine effects** such as thyroid disruption, impaired reproductive function, altered insulin signalling, and even neuroendocrine changes.

✓ PM2.5/PM0.1 themselves are **vectors and amplifiers** of endocrine disruption rather than primary EDCs.

Epidemiological studies have indicated the association of $PM_{2.5}$ exposure with respiratory and cardiovascular diseases.

•Exposure to $PM_{2.5}$ induces oxidative stress, inflammation, and immune responses in humans.

•$PM_{2.5}$-bound chemical components exhibit greater toxicity and immunotoxicological effects.

•Noncoding RNA (ncRNAs) may play a role in $PM_{2.5}$-related effects through oxidative stress and gene disruption within cells.

•Potential biomarkers following $PM_{2.5}$ exposure include IL-4, IL-6, IL-13, TNF-α, IL-17, and IFN-γ.

Environmental Advances, 2024, 18, 100603

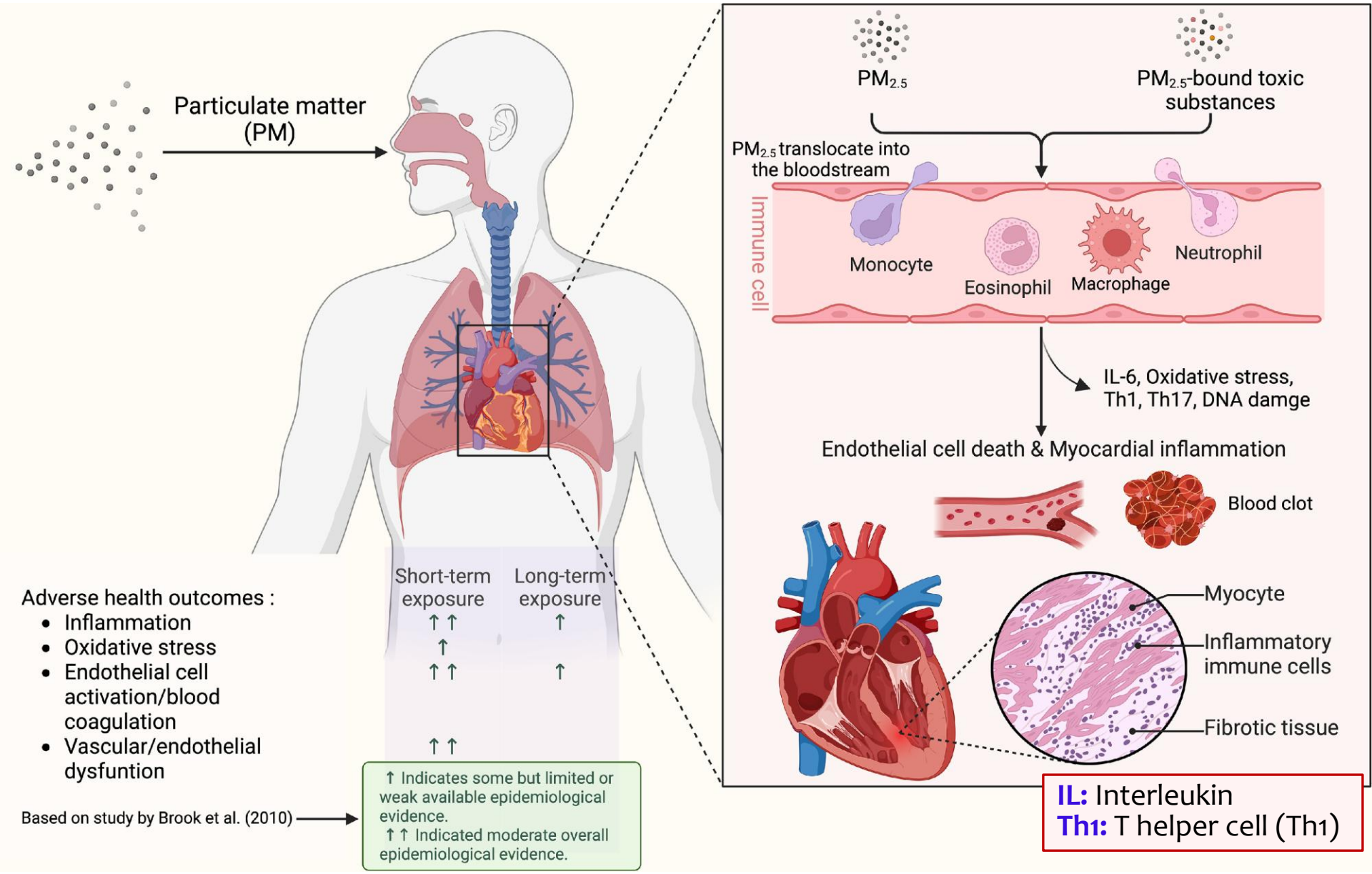


Diagram summarising current hypotheses regarding cardiac pathophysiology of $PM_{2.5}$ progression to cardiovascular disease, created with BioRender.com.

Interleukins (ILs) are a group of naturally occurring, low-molecular-weight proteins, type of cytokines that act as chemical messengers in immune system, regulating growth, differentiation, and activation of immune cells.

IL-1α (**Interleukin-1α**) stimulates the activity of genes involved in inflammation and immunity, making it a crucial component of the body's response to infection and injury.

IL-1β is a powerful pro-inflammatory cytokine protein that plays a crucial role in the immune system's response to infection and injury, but also contributes to chronic inflammatory diseases.

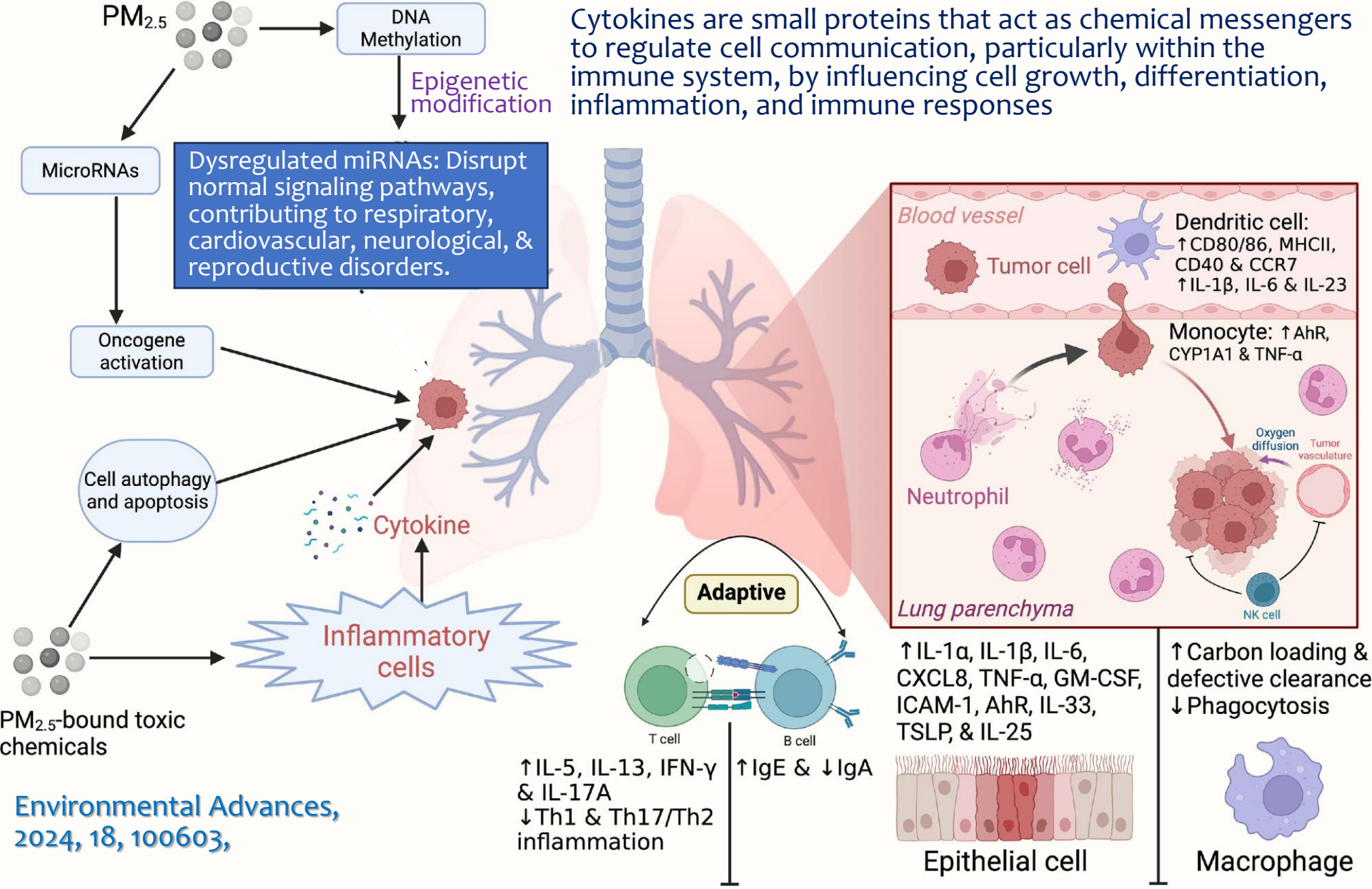
IL-3, or Interleukin-3, is a cytokine that promotes the growth and development of various blood cells in the bone marrow, including hematopoietic stem and progenitor cells, and also plays a role in immune responses and the central nervous system.

IL-5 is a cytokine, a type of protein, that plays a crucial role in immune responses, particularly in the development and function of eosinophils.

IL-6 (Interleukin-6) is a cytokine with diverse effects, acting as a pro-inflammatory molecule in cases of infection and tissue damage, but also as an anti-inflammatory myokine secreted by muscles during exercise. Dysregulated IL-6 levels are linked to inflammatory, autoimmune, and cancer diseases, making it a target for therapies such as IL-6 receptor inhibitors.

IL-7, or Interleukin-7, is a cytokine that is crucial for the development and survival of lymphocytes, particularly T and B cells. It is essential for immune system homeostasis, playing a vital role in both the growth of immature lymphocytes and the maintenance of mature immune cell populations.

"**Th1**": T helper cell (Th1) produces messenger protein, involved in cell-mediated immunity, producing interferon-gamma (IFN-γ) to combat intracellular pathogens like viruses and bacteria. "**TH-17**" cells are crucial for host defence against fungal and extracellular bacterial infections but also play a significant role in autoimmune and inflammatory diseases.



Environmental Advances, 2024, 18, 100603,

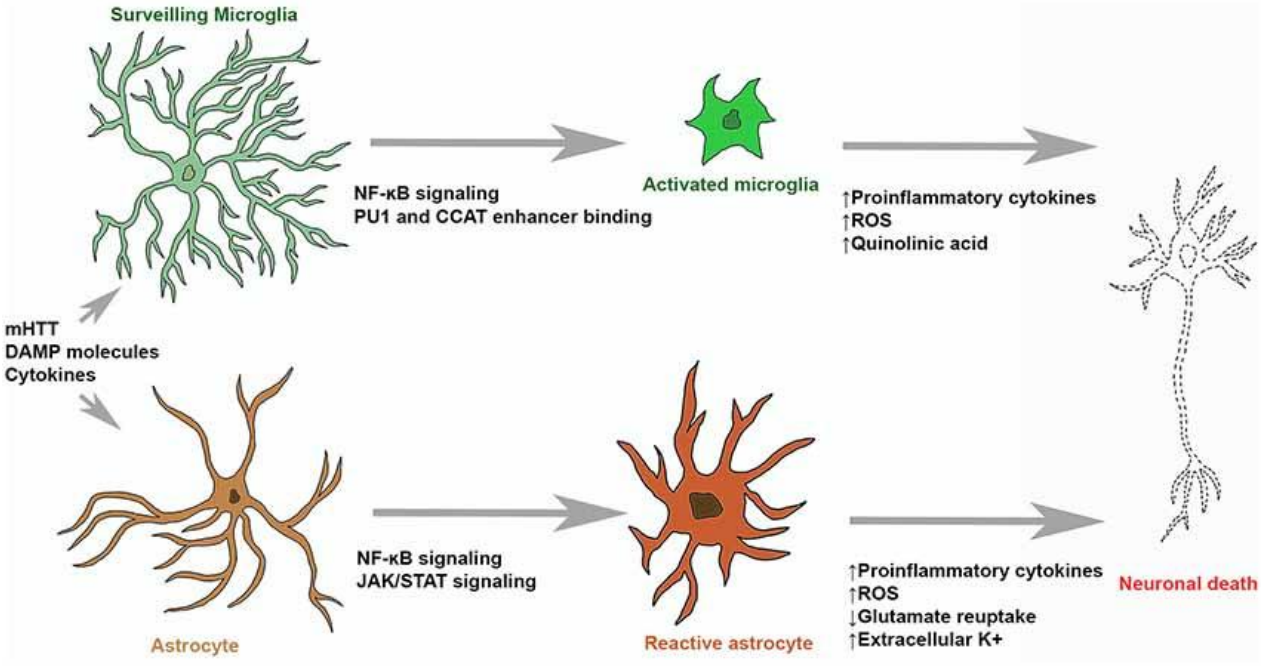
Pathways of PM2.5 in the pathogenesis of chronic airway inflammation via immune response at the respiratory epithelium cell, created with BioRender.com.

Microglial cells: Resident immune cells of the central nervous system (CNS). Functions: Immune surveillance, Synaptic remodelling, Tissue repair, and neuroinflammation.

Astrocytes are glial cells of the central nervous system that provide metabolic, structural, and homeostatic support to neurons. They regulate the blood–brain barrier, maintain neurotransmitter balance by clearing excess glutamate and GABA, supply energy, and facilitate synapse formation and function. Additionally, they buffer extracellular potassium and respond to injury by forming glial scars.

Gamma-Aminobutyric Acid (GABA): Primary inhibitory neurotransmitter in the central nervous system (CNS) of mammals, and plays a crucial role in reducing neuronal excitability and calming the nervous system

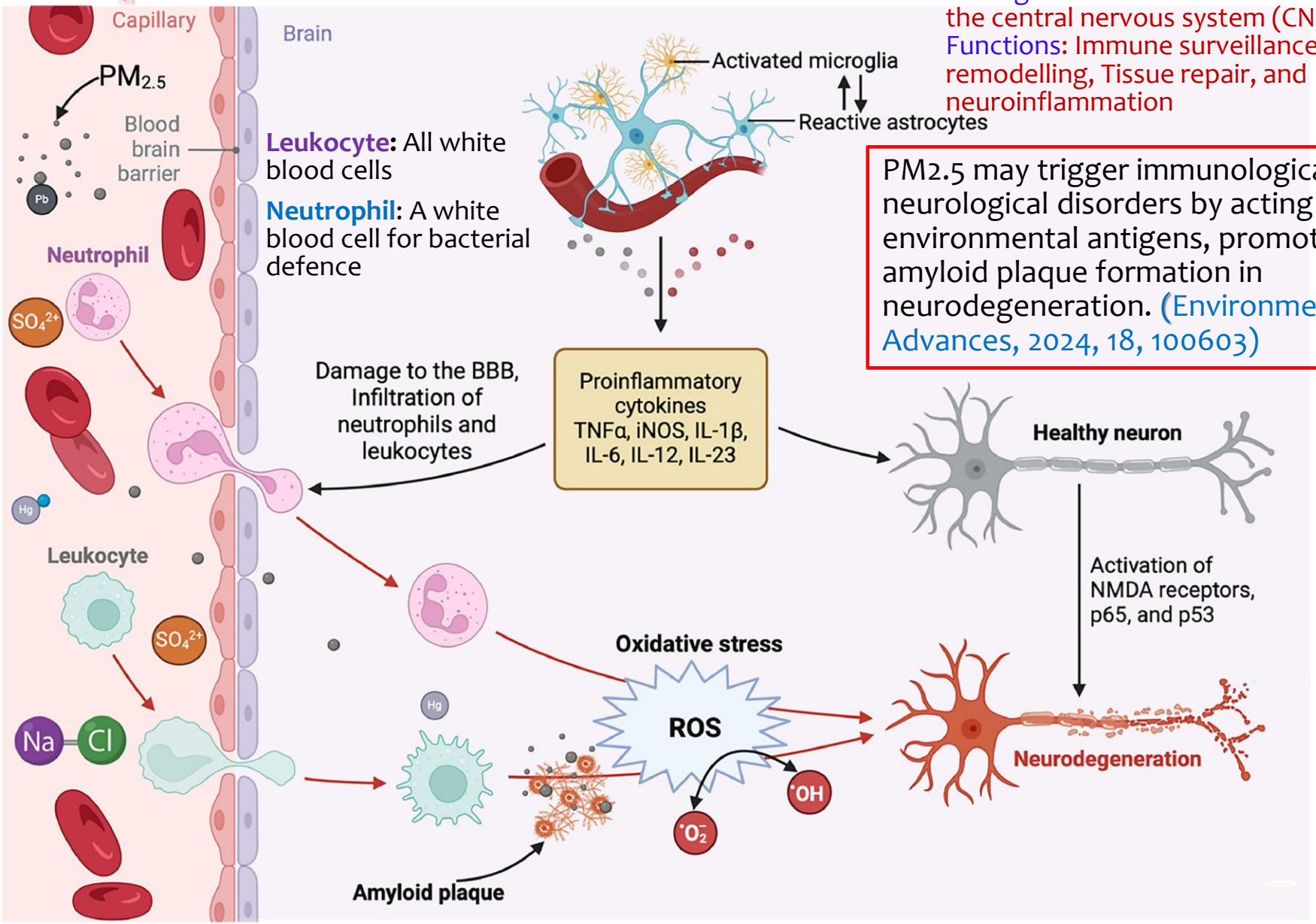
Environmental Advances, 2024, 18, 100603,



Mechanisms – Immunological Disorders / Neurological Disorders

Roles of Astrocytes and Microglia in Neurodegeneration

Microglial cells: Resident immune cells of the central nervous system (CNS).
Functions: Immune surveillance, Synaptic remodelling, Tissue repair, and neuroinflammation



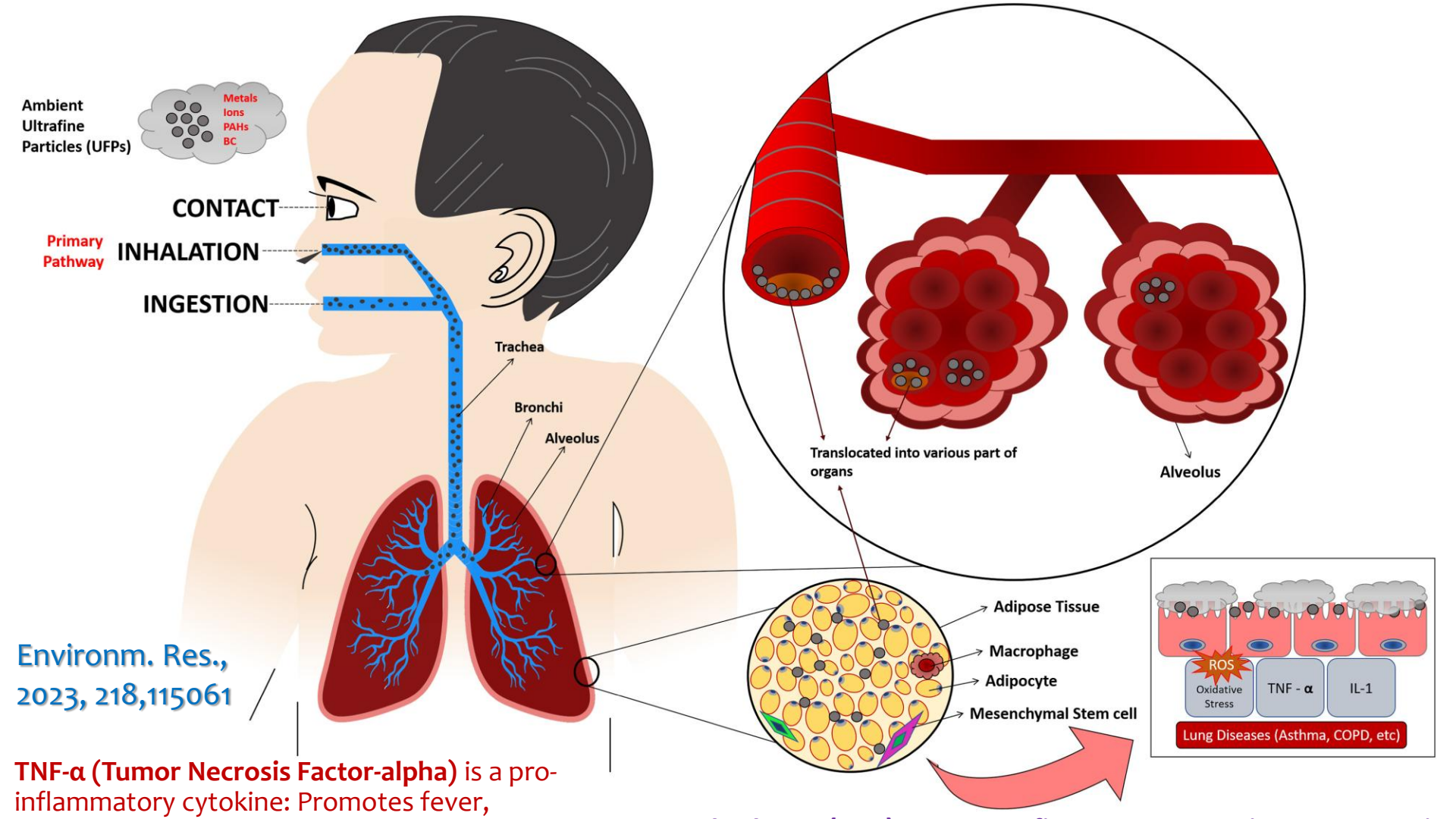
Leukocyte: All white blood cells

Neutrophil: A white blood cell for bacterial defence

PM2.5 may trigger immunological and neurological disorders by acting as environmental antigens, promoting amyloid plaque formation in neurodegeneration. (Environmental Advances, 2024, 18, 100603)

Impacts on ultrafine particle (PM0.1):

Ultrafine particles, PM0.1, can migrate into the brain through the olfactory bulb, the neural structure responsible for the sense of smell. Ultrafine particles also produce cytokines that inflame the lungs or the nasal epithelium and further attack brain cells.



Environm. Res., 2023, 218,115061

TNF-α (Tumor Necrosis Factor-alpha) is a pro-inflammatory cytokine: Promotes fever, inflammation and cell apoptosis. Elevated level: induces autoimmune and inflammatory diseases.

Interleukin-1 (IL-1) is a pro-inflammatory cytokine in animals that induces an immune response, fever, and inflammation.