Sustainability and Chemistry
CH5106: L4

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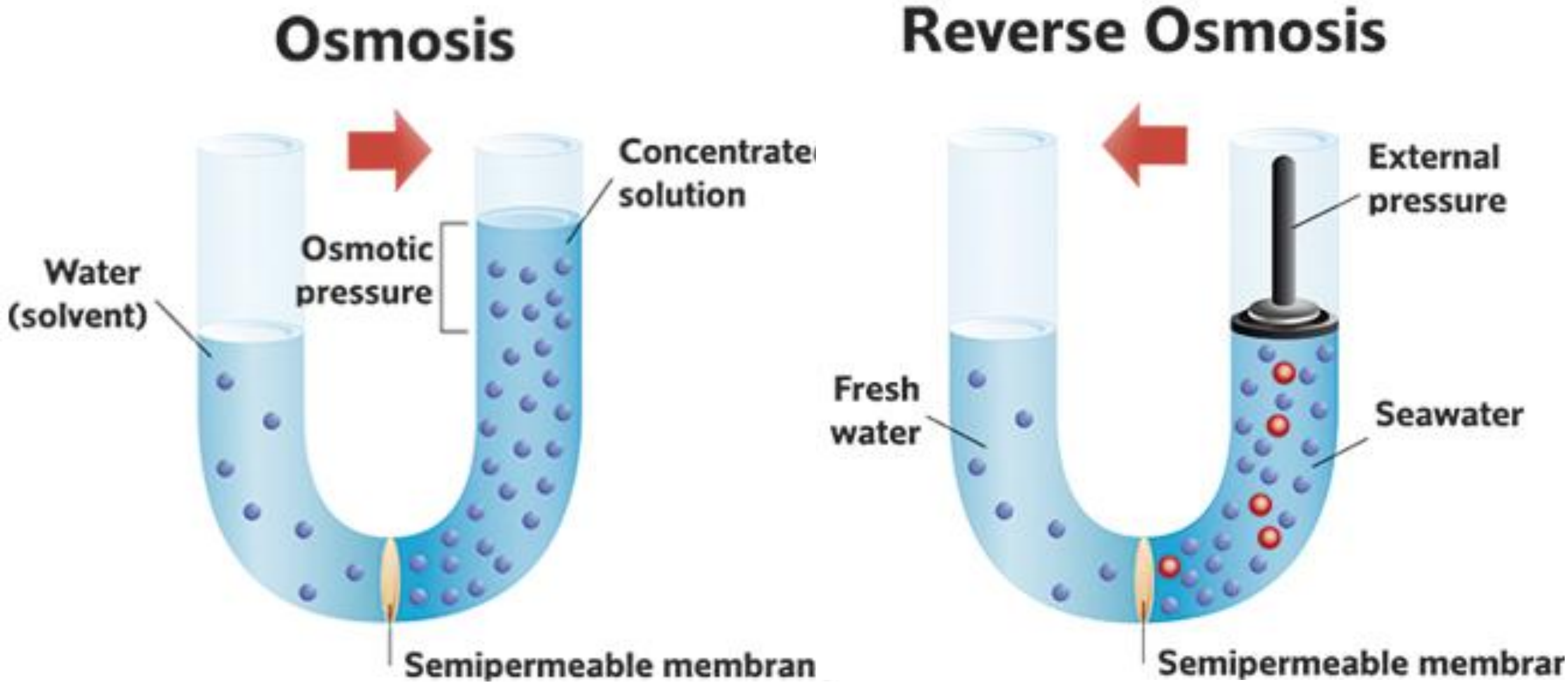


Diagram of osmosis in a U-shaped tube through a dialysis membrane that separates two solutions having different solute concentration.

Osmosis is a process that is fundamental to the physiology of all living things. It is the selective transport of water across a semipermeable membrane from high to low chemical potential caused by a difference in solute concentrations and/or hydrostatic pressures.

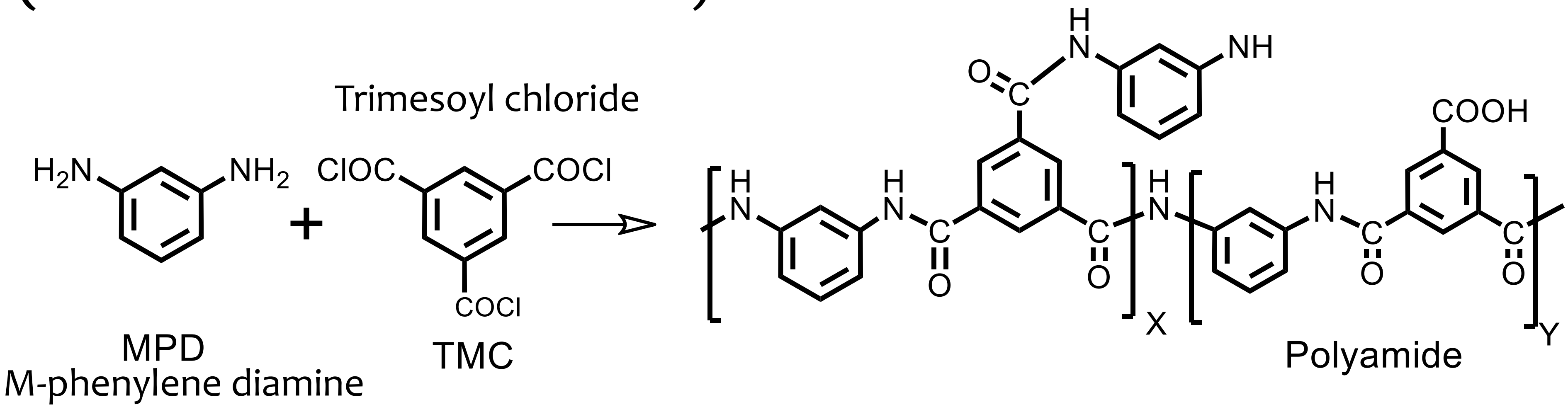
What is a TFC Membrane?

•**TFC membranes** are layered structures, typically made of:

- A **polyamide thin film** (active layer)
- A **microporous polysulfone layer**
- A **polyester support fabric**

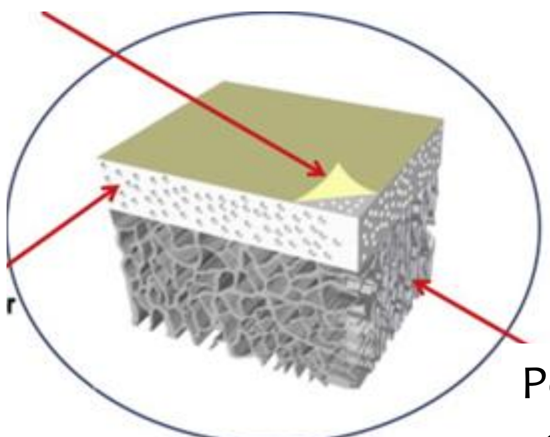
Used primarily for **RO filtration,** they are highly effective for desalination and wastewater treatment.

Thin Film Composite membranes (for Flat Sheet Membrane)



Membrane performance under BW condition: 50-65 l/m^2hr, salt rejection 97-98% at 225-250 psi applied pressure……*feed water quality dependent*

Active layer (< 200 nm) of Polyamide



Polysulphone Layer

Polyester web ~120 μm

Steps:

Ultrafiltration membrane casting on polyester fabric following phase separation method

Polyamide coating following *in situ* interfacial polymerization reaction

Polyamide layer in TFC membrane:

Polyamide membranes are renowned for their exceptional salt rejection performance, often achieving rates exceeding 99%. This high selectivity is primarily due to the dense, highly cross-linked polyamide layer, which minimizes pore size and enhances ion exclusion. At the same time, these membranes offer high water permeability, enabling efficient throughput during filtration. The optimized balance between selectivity and permeability is a hallmark of polyamide thin-film composite (TFC) membranes, making them a preferred choice in reverse osmosis and other advanced water treatment applications.

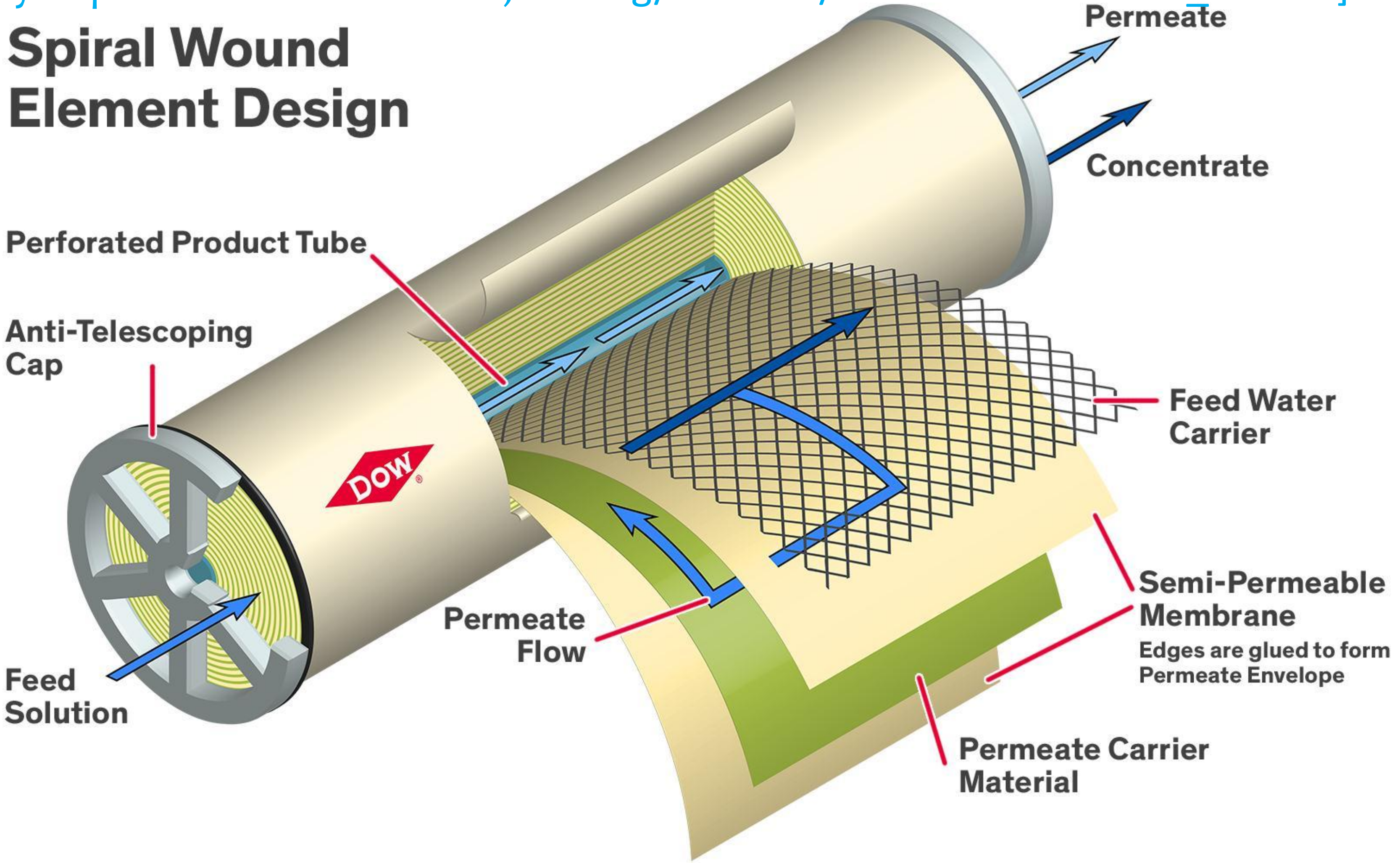
In a Thin-Film Composite (TFC) membrane, the polysulfone (PSf) layer acts as a porous support structure. It provides mechanical strength and stability to the overall membrane, especially under pressure. The PSf layer is typically made via phase inversion, creating a porous structure that allows for water or other permeate to pass through while supporting the thin, selective polyamide (PA) layer on top.

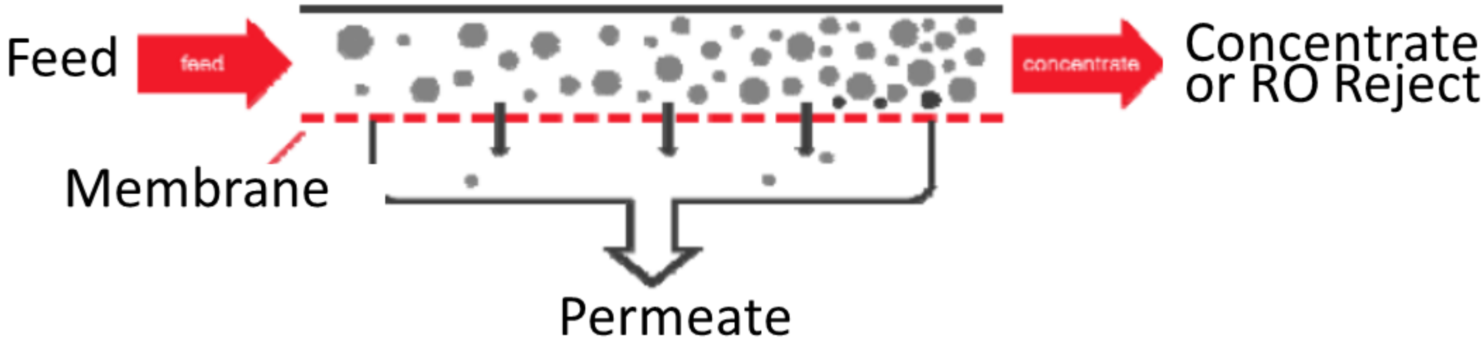
Role of the Polysulfone Layer in a TFC Membrane:

- ✓ Microporous Support Structure: The polysulfone layer provides mechanical strength and structural support to the ultra-thin, selective polyamide top layer, which is otherwise too fragile to function alone. Its microporous architecture allows water to pass through freely without offering significant resistance.
- ✓ Permeability Facilitator: The porous structure ensures minimal interference with water flux, enabling high permeability while maintaining the integrity of the membrane.
- ✓ Chemical and Thermal Stability: Polysulfone is known for its excellent chemical resistance, especially to oxidants and organic solvents, and for maintaining dimensional stability under elevated temperatures and pressure conditions.
- ✓ Substrate for Polyamide Layer Formation: During the interfacial polymerization process, the polyamide active layer is formed on top of the polysulfone layer. The PSf layer provides the ideal surface morphology and chemical compatibility for this reaction to occur effectively.
- ✓ Intermediate Layer Between Polyester and PolyamideThe polysulfone acts as a functional bridge between the porous polyester base layer (for overall mechanical stability) and the selective polyamide layer (for salt rejection).

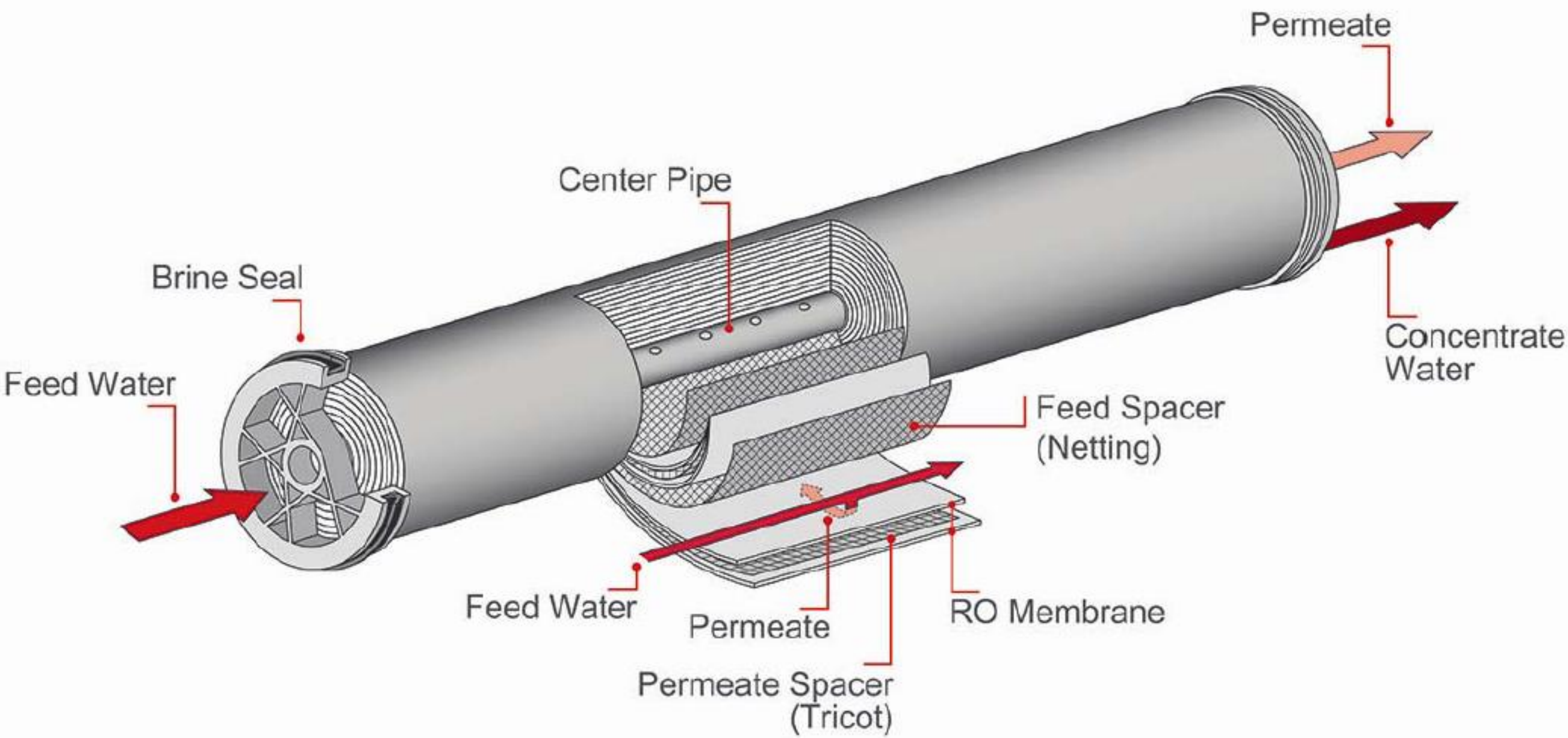
In the context of membranes, convective flow refers to the transport of fluid (pure solvent or solution) across a porous membrane, which is driven by the applied pressure. Convective transport is the main mode of transport in microfiltration and ultrafiltration processes; it may also contribute to the transport in diffusion dialysis if the pressure is applied.

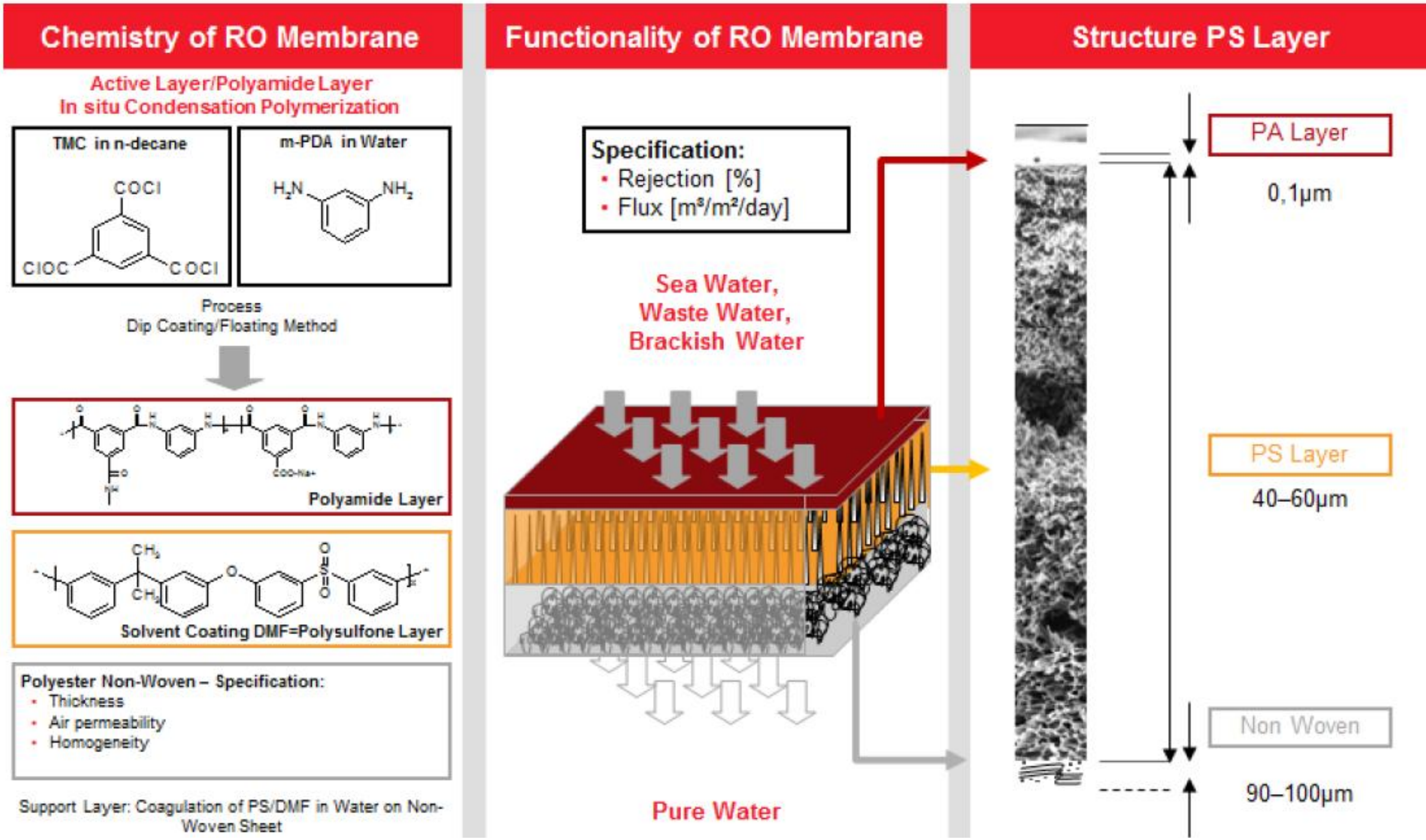
[Encyclopaedia of Membranes; doi.org/10.1007/978-3-642-40872-4_1994-1]





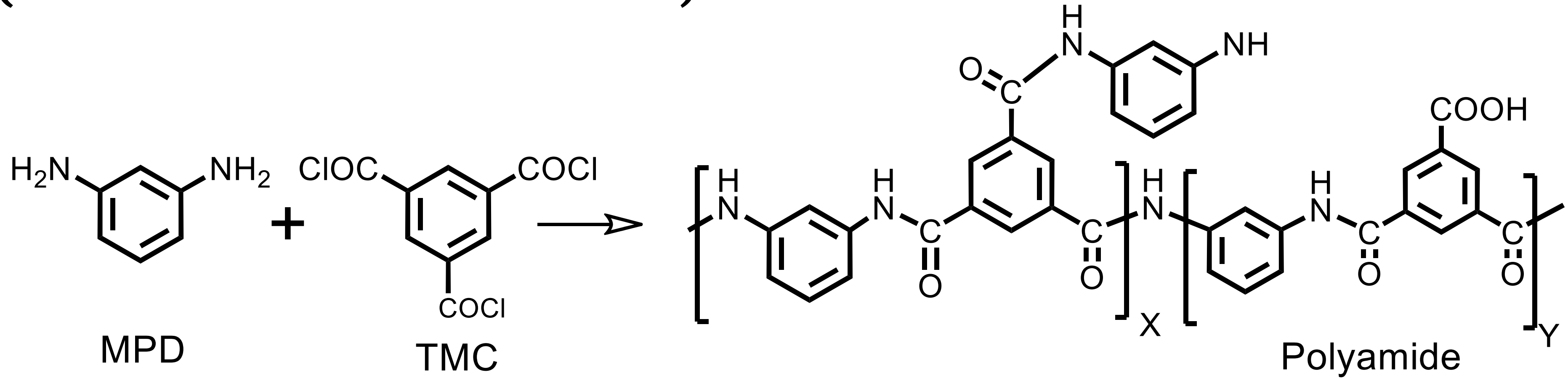
Typical spiral-wound element construction

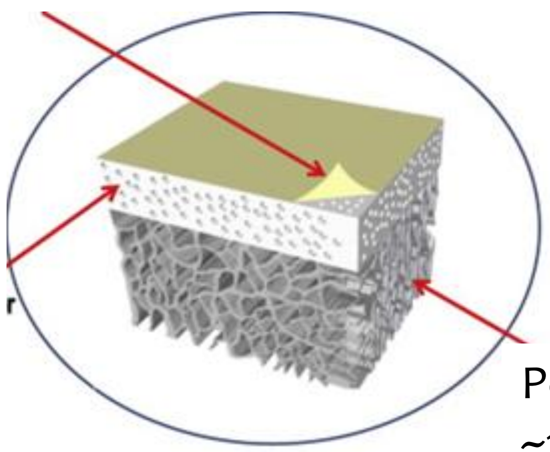




Chemistry of RO Membrane
Active Layer/Polyamide Layer
In situ Condensation Polymerization
TMC in n-decane
COCl
ClOC
COCl
m-PDA in Water
H2N
NH2
Process
Dip Coating/Floating Method
COO-Na+
Polyamide Layer
CH3
CH3
O
Solvent Coating DMF=Polysulfone Layer
Polyester Non-Woven – Specification:
• Thickness
• Air permeability
• Homogeneity
Support Layer: Coagulation of PS/DMF in Water on Non-Woven Sheet
Functionality of RO Membrane
Specification:
• Rejection [%]
• Flux [m³/m²/day]
Sea Water,
Waste Water,
Brackish Water
Pure Water
Structure PS Layer
PA Layer
0,1µm
PS Layer
40–60µm
Non Woven
90–100µm

Thin Film Composite membranes (for Flat Sheet Membrane)





Membrane performance under BW condition: 50-65 l/m²hr, salt rejection 97-98% at 225-250 psi applied pressure……*feed water quality dependent*

Steps:

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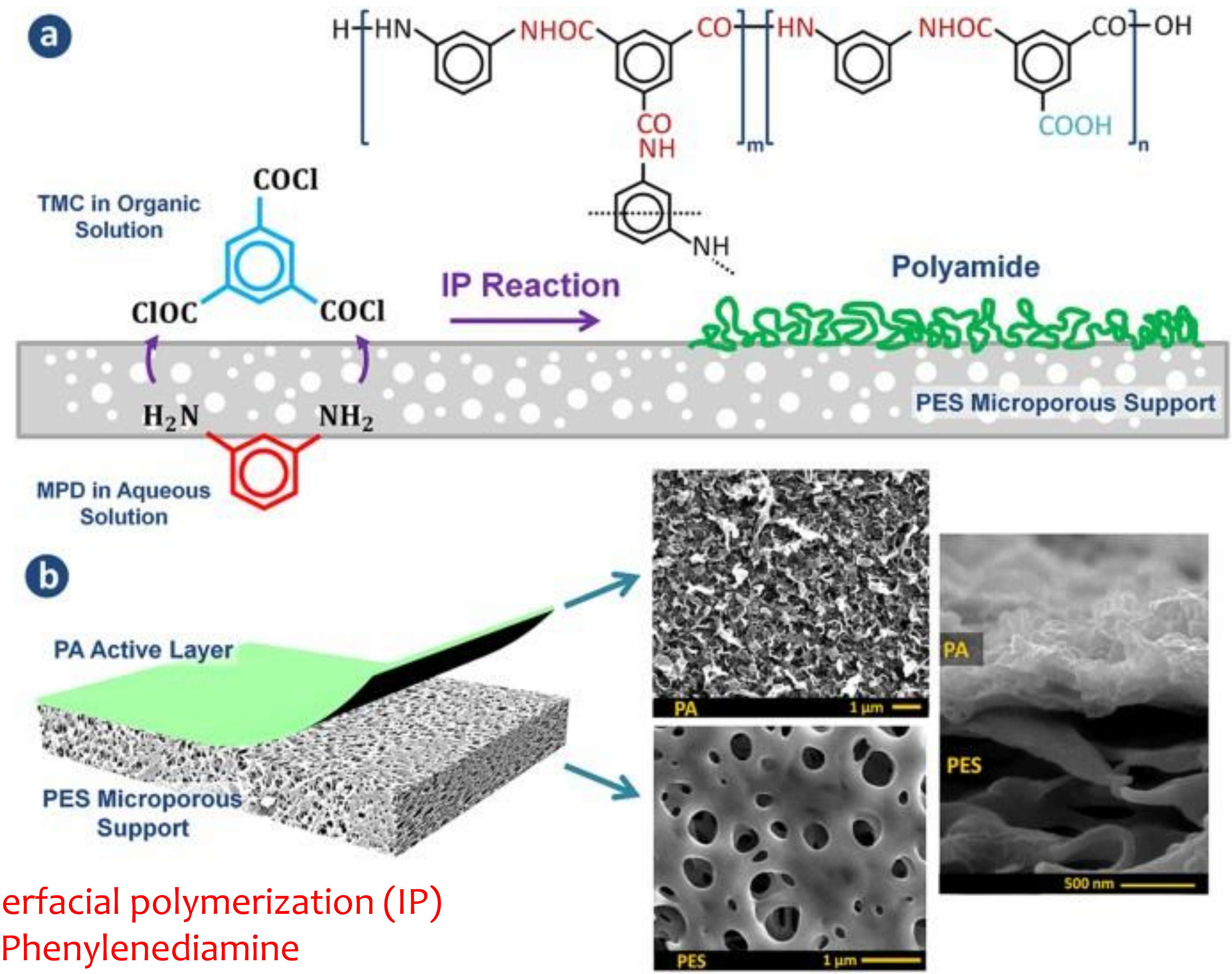


interfacial polymerization (IP)
m-Phenylenediamine
polyethersulfone (PES)

Sci Rep 2016, 6, 22069

Permeate flux describes the quantity of permeate produced during membrane separation per unit of time and RO membrane area. The flux is measured in liters per square meters per hour (lmh) or in gallons per square feet per day (gfd).

The flux is defined by: $J_v = Q_p / S$

J_V: permeate flux, S: area of the membrane, Q_p: permeate flow rate

Salt rejection is a percentage which describes the amount of solute retained by the RO membrane.

The retention is given by: $R = (1 - C_p/C_{ave}) \times 100$

R: rejection, Cp: permeate concentration, C_f: feed concentration
C_c: concentrate concentration
C_{ave} : average feed concentration

$$C_{ave} = (C_f + C_c) / 2$$

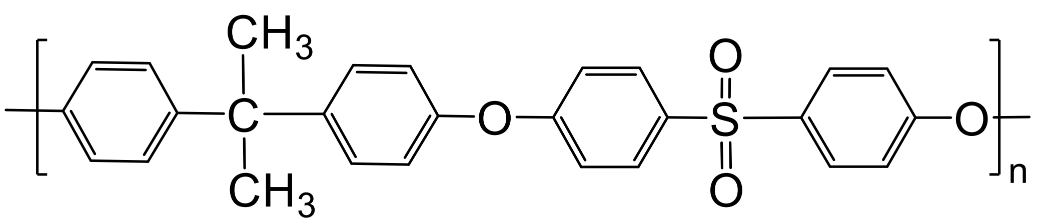
The recovery rate is defined as the fraction of the feed flow which passes through the membrane. It is usually expressed in percentage.

$$Y = Q_p / Q_f$$

Y: Recovery rate; Q_p: permeate flow rate; Q_f : feed flow rate

Polysulfone (PSU) repeating unit.

(Commercial name)



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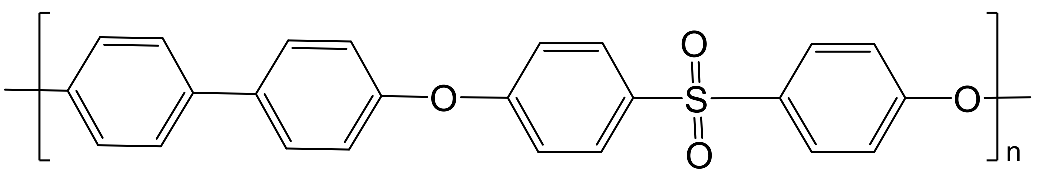
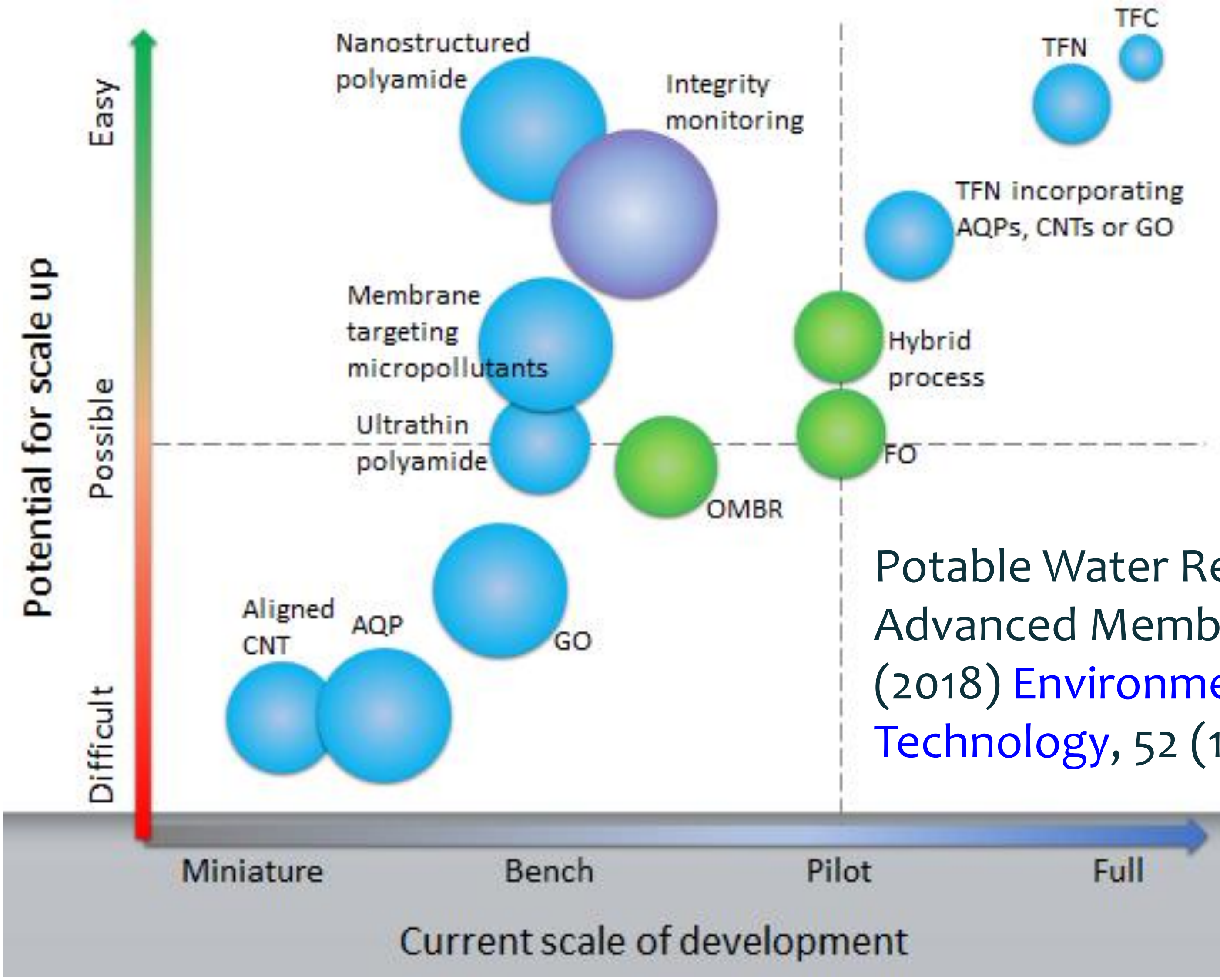


Radel

Polysulfone (PSU) membranes have been widely applied in microfiltration and ultrafiltration processes due to their excellent properties, such as chemical inertness across the entire pH range (pH 2-13), compressive strength, and thermal stability (~ 170°C). Despite these advantages, the application of PSU membranes in filtration processes has often been restricted due to their hydrophobic nature, which results in serious membrane fouling and a reduced permeate flux. Moreover, PSU membranes suffer from poor mechanical properties.

Findings from various individual studies emphasized that the membrane pore size and surface porosity mostly governs PSU membrane morphology, which enhances membrane performance and reduces membrane fouling.



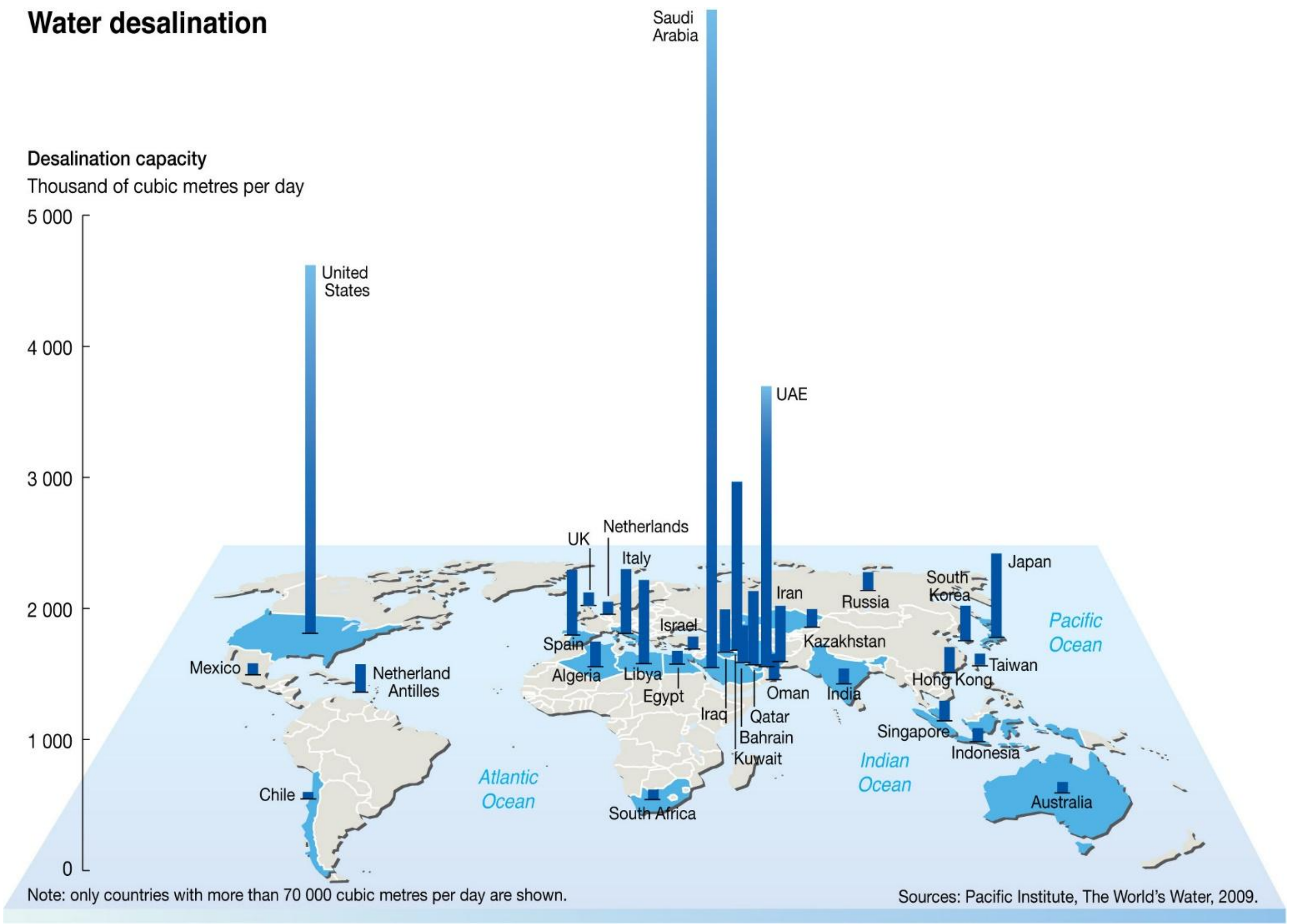
(TFN) Thin film nanocomposite

Potable Water Reuse through Advanced Membrane Technology (2018) Environmental Science and Technology, 52 (18), pp. 10215-10223

Outlook of water reuse technologies. Both axis have the usual meaning.

Size of the sphere represents the potential impact of a particular technology--larger sphere indicates enhanced reliability, reduced cost, and energy consumption, and/or improved water quality.

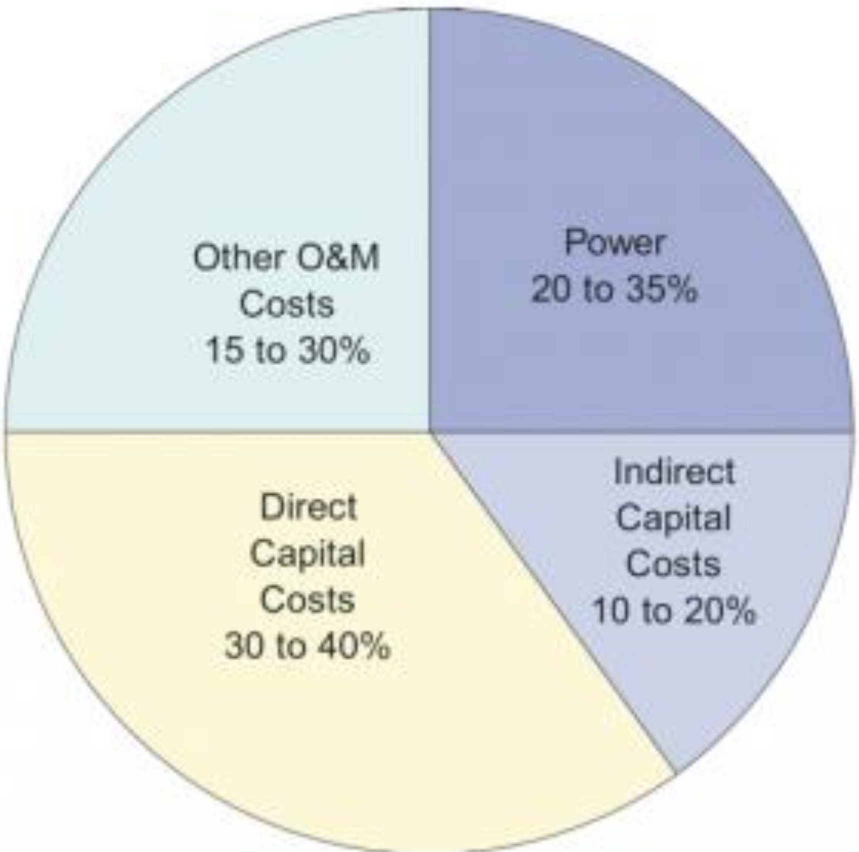
- Per person water availability:
  - 2309 cubic meter (1991)
  - 1902 cubic meter (2001)
  - 1401 cubic meter (2025)
  - 1191 cubic meter (2050)
- Indian desalination market worth: $660 million ($1.9bn by 2019)
- Indian Coast line : 7,517 km



http://www.iwa-network.org/desalination-past-present-future/

Cutting the costs

Energy is one of the largest costs associated with seawater desalination. Figure shows a typical breakdown of the seawater desalination costs



Advances in technology and equipment have resulted in a reduction of 80 percent of the energy used for water production over the last 20 years. Today, the energy needed to produce fresh water from seawater for one household per year (~2,000 kW/yr) is less than that used by the household's refrigerator

INTERNATIONAL WATER ASSOCIATION, NIKOLAY VOUTCHKOV AUGUST 17, 2016

Reverse Osmosis based processes

Brackish Water Desalination: ~3000 – 7000 ppm

One Step Process

Working pressure: 225 - 250 psi (or ~ 30 bar pressure)
Water recovery: ~ 65%
Capacity: 500 - 10000 LPH
Cost: ~ Rs.0.07/- per L
Rejection: > 98% (~ 200-300 ppm)

Sea Water Desalination: ~30,000 – 35,000 ppm

Two Step Process

Working pressure: 800 plus psi (or ~60 bar pressure)
Water recovery: ~ 55%
Capacity: 500 - 10000 LPH
Cost: ~ Rs. 0.12/- to 0.15/- per L
Rejection: > 98% (~200 – 300 ppm)

Electro dialysis based processes

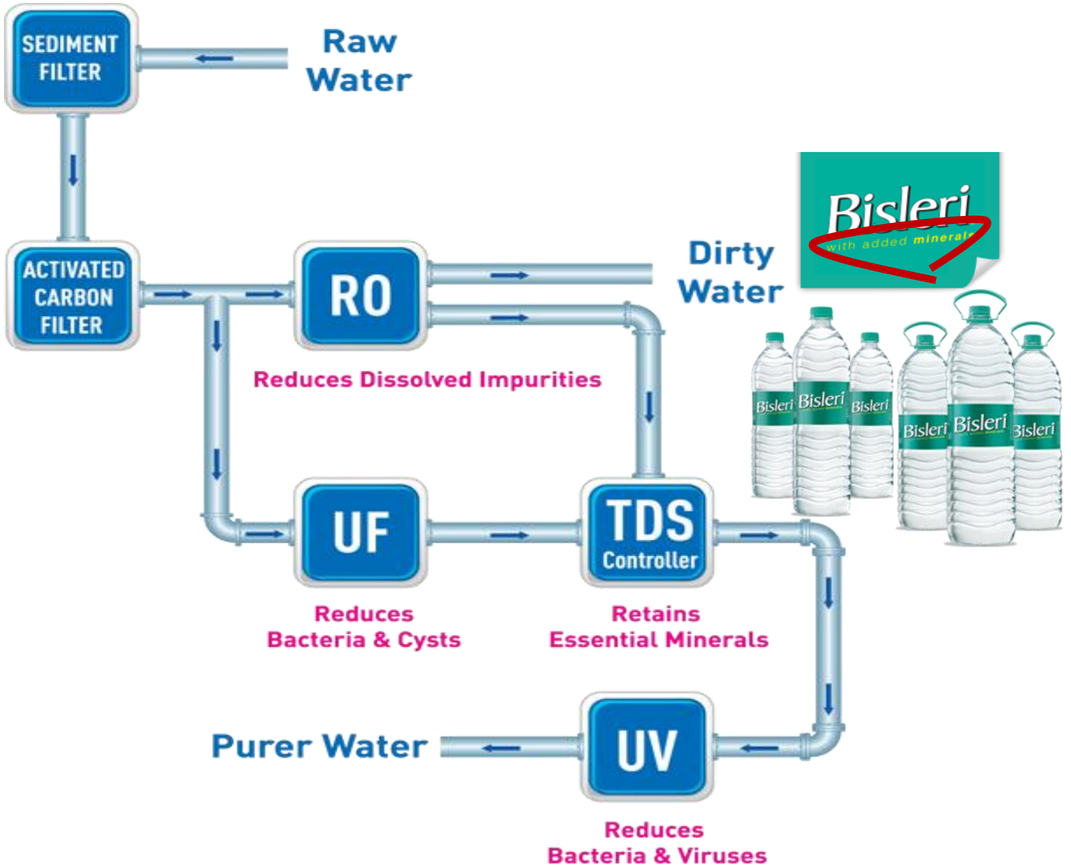
Brackish Water Desalination: < 3000 ppm

~ 140 - 200 mAmp current
Water recovery: ~ 85%
Capacity: ~ 350 - 400 LPH [for 40 cm x 80 cm stack]
Cost: ~ Rs.0.04/- per L [For Solar panel driven]
TDS in water: > 200-250 ppm

During desalination, the salinity is lowered – which is desired – but the concentrations of nutritious constituents may also be reduced excessively—which is not desired.
Nature 452 (2008) 301.

Remineralisation is one approach to correct the imbalance but this is not practiced always.
Water Sci. Technol. 49 (2003) 69; 55 (2007) 127.

Nutritious constituents depletion is an issue in water obtained through RO process.
Science 318 (2007) 920.



ED process with mono-valent selective ion-exchange membranes can be used for the retention of nutritious bulky ions (HCO_3^-/bivalent ions) to produce nutritious drinking water during brackish water desalination.

Environmental Science & Technology
Comment
Environ. Sci. Technol. 2019, 53, 3999−4000

The Unintended Consequences of the Reverse Osmosis Revolution

As reverse osmosis creates additional fluoride-deficient drinking water supplies, **public health experts will have to pay more attention to the need to augment dietary fluoride sources. This issue is particularly important in lower income communities,** where fluoride containing toothpaste is less common. For example, failure to appreciate the impact of reverse osmosis on fluoride led to decreases in height and increases in caries among children in communities in China where reverse osmosis systems had been installed at primary schools.

About 10 years ago, **epidemiologists reported increased rates of suicide in communities where lithium concentrations in drinking water are low.** Although not all of the subsequent studies supported the lithium deficiency hypothesis, **the concentrations of lithium in desalinated seawater are at the low end of the range reported in places where increased suicide rates have been observed**.

Journal of Affective Disorders Part **A**, 2022, 298, 516-521

Magnesium in water produced by this process has resulted in deficiencies in magnesium that increase the risks of heart disease. When this problem first came to light, water providers in Israel initiated an effort to develop cost-effective and reliable approaches for introducing magnesium during remineralization.

Desalination, 2018, 426, 88-96

The unsustainability issue related to End-of-life Thin Film Composite (TFC) membrane-based water treatment modules—commonly used in RO systems.

By 2025, over 2 million end-of-life (EoL) RO membrane modules are expected to be generated worldwide each year. While landfill and incineration remain the most common disposal methods, chemical recycling and the repurposing of EoL RO membranes are becoming more popular as sustainable alternatives.

Membranes 2025, 15, 217.

1. Non-Biodegradability and Plastic Waste

- The materials used (e.g., **polyamide, polysulfone, polyester**) are **not biodegradable**.
- Discarded membranes contribute to the **growing volume of plastic and composite waste**, which accumulates in landfills.

2. Lack of Recycling Infrastructure

3. Chemical Contamination Risks

- Membranes used in industrial RO may be contaminated with:
    - **Heavy metals**
    - **Organic compounds**
    - **Scaling agents**
- Improper disposal can lead to **leaching of toxic substances** into soil and water systems.

High Replacement Frequency

- RO membranes typically have a **lifespan of 3–5 years** depending on application.
- **Frequent replacement** leads to consistent waste generation, raising sustainability concerns for large-scale systems.

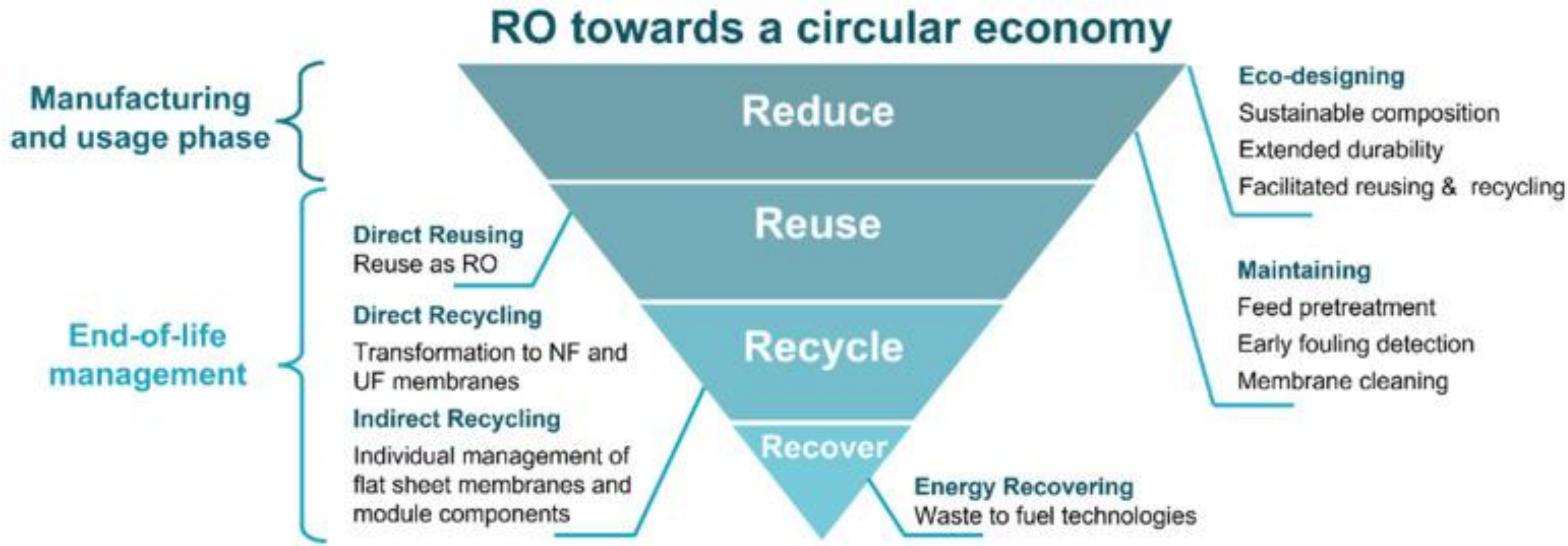
5. Carbon Footprint

- The **manufacturing process** of TFC membranes involves:
  - High energy input
  - Use of hazardous chemicals (e.g., solvents like dimethylformamide)
- End-of-life incineration contributes to GHG emissions.

Potential Solutions (for Sustainable Management)

1. **Membrane Reuse:** Repurposing out-of-life RO membranes for **lower-pressure applications** such as: 1. Greywater recycling
   2. Pre-treatment filters

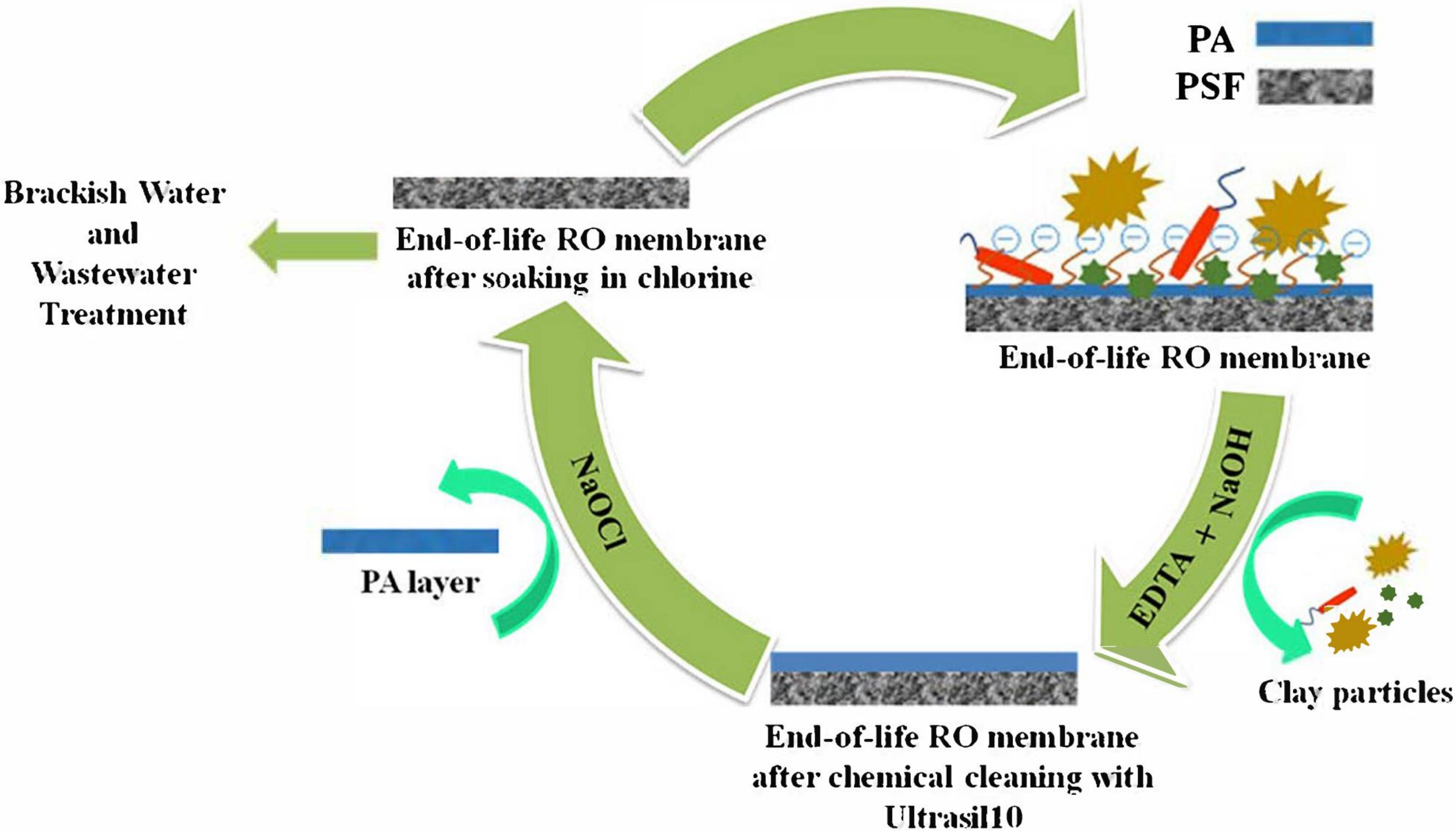
1. **Recycling Initiatives**: Development of **mechanical or chemical recycling technologies** to recover polymers or convert membranes to fuel.
2. **Eco-Design**: Innovation toward **monomaterial membranes** or **bio-based alternatives** for easier recycling and reduced environmental impact.
3. **Circular Economy Models**: Manufacturer take-back schemes and **extended producer responsibility (EPR)** for end-of-life management.



Possible pathways of waste hierarchy to be implemented by membrane technology

Membranes (Basel). 2022 Sep 7;12(9):864

Nanofiltration ~ < 8 nm
RO ~< 1nm



Membranes **2025,** 15(7), 217

Membrane Technologies Water purification/desalination

~ 0 ppm	400-700 ppm	700-1500 ppm	1500- < 10000 ppm	> 10000 ppm	Sea water

Ultrapure water Electro-deionization Technology Resistivity: 18.2 MΩ cm

Microfiltration: Hollow fiber technology. Ultrafiltration: Flat sheet ultra-filter membrane and modules.

Nano-filtration: membrane and modules: Spiral module 4040 (low pressure).

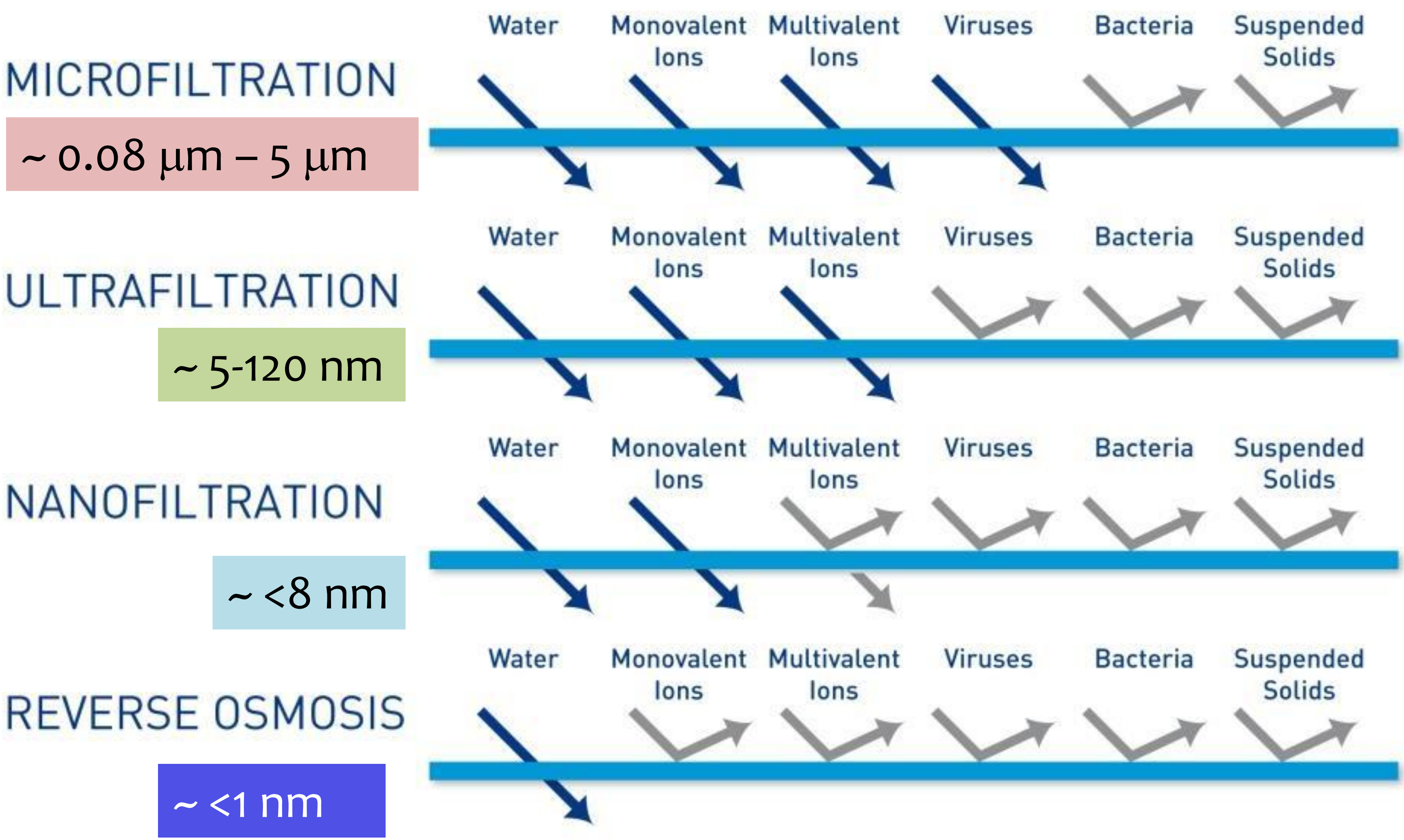
Brackish water desalination: Medium pressure BW TFC FS RO BW 4040, 8040

Sea water desalination: High pressure SW TFC FS RO 8040

Ion exchange membrane based electrodialysis for water desalination

Specific ion selective resin technology for fluoride and arsenic removal.

TYPE OF MEMBRANES AND CHARACTERISTICS



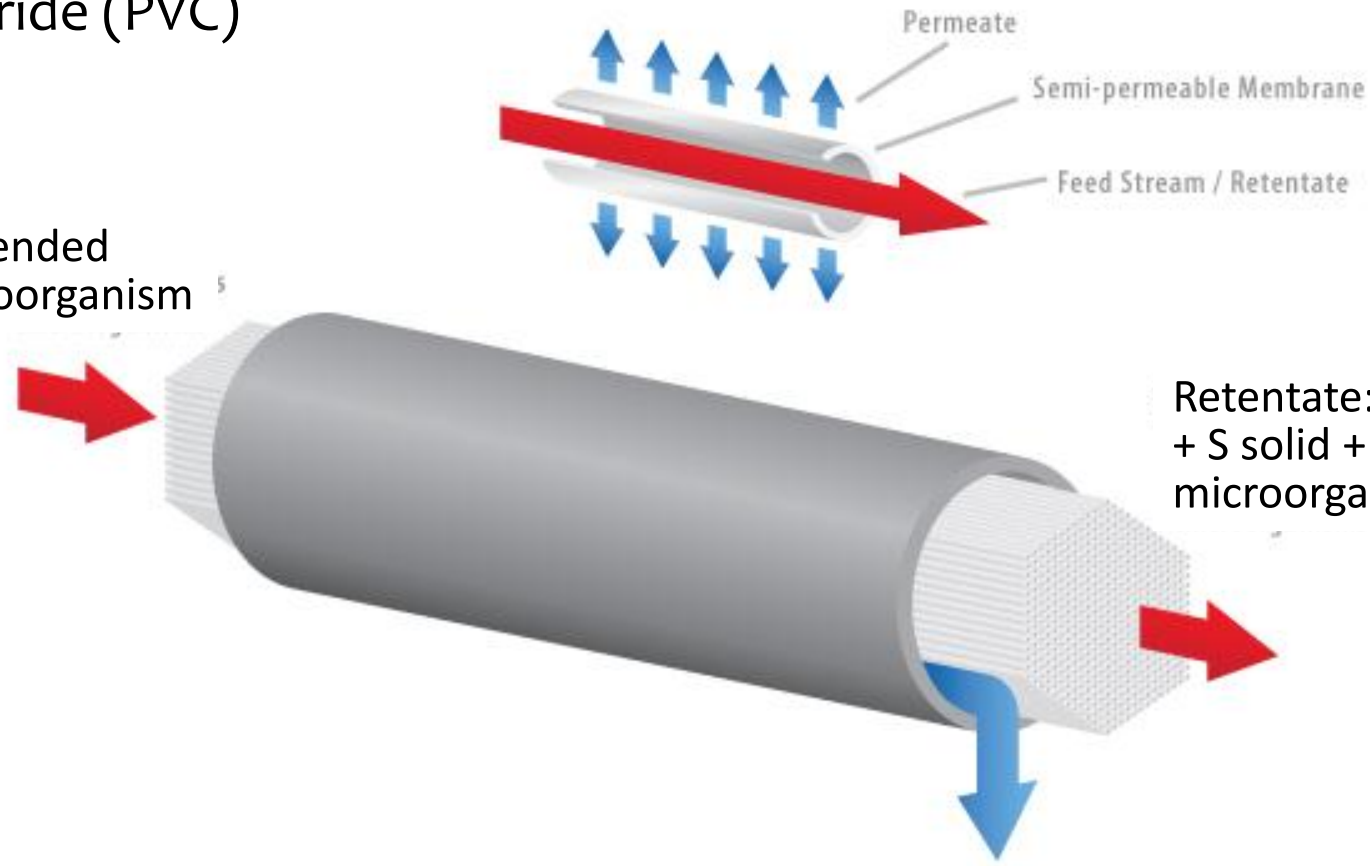
Major Research Focus: Potable Water through desalination of sea water/ brackish water/ pathogen removal/ removal of contaminants like Fluoride/ Arsenic/ iron/ etc

Hollow fiber membrane:

Inside a hollow fiber membrane water filter, hundreds of tubes—resembling tiny straws—are bundled together to create a filter matrix. The walls of these tubes are filled with microscopic pores, or holes. As you pump water through the walls of these fibers, any microbiological threats lurking in the backcountry's cool, crisp water sources are trapped inside. This removal method is referred to as size exclusion. That is, the pores in the fibers' walls are simply too small for the pathogens to fit through, but water still can. These pores so microscopic, they're invisible to the naked eye.

Understanding pore size is important because it indicates the size of the microbes a particular filter or purifier is designed to remove. A backpacking filter (i.e., a microfilter) should feature a pore size of 0.2 microns. This will remove virtually all waterborne bacteria and protozoa. Hollow fiber technology should feature a pore size of 0.02 to remove viruses as well.

The most common polymers in membrane synthesis are cellulose acetate, Nitrocellulose, and cellulose esters (CA, CN, and CE), polysulfone (PS), polyether sulfone(PES), polyacrilonitrile (PAN), polyamide, polyimide, polyethylene and polypropylene (PE and PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyvinylchloride (PVC)

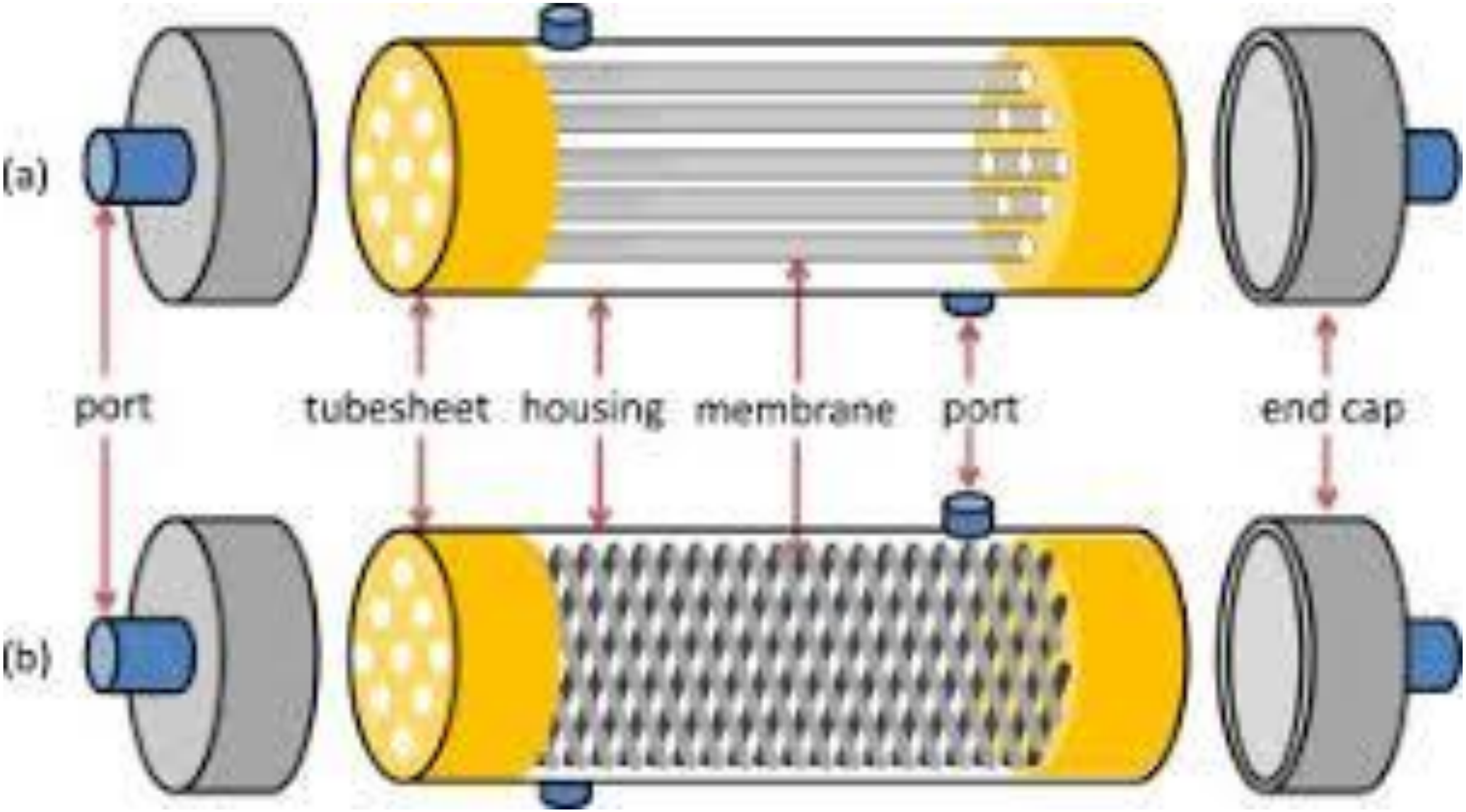


Feed stream
Water; suspended
Solid & microorganism

Retentate: water
+ S solid +
microorganism

Permeate: Clean water

Model configuration –
Hollow Fiber Membrane



(a)
(b)
port
tubesheet
housing
membrane
port
end cap

How are Hollow Fiber *Membranes* (HFM) Made?

The method used to produce Hollow Fiber membranes is based on the type and molecular weight of synthetic polymer used. The most common production method is referred to a spinning. There are four general types of spinning.

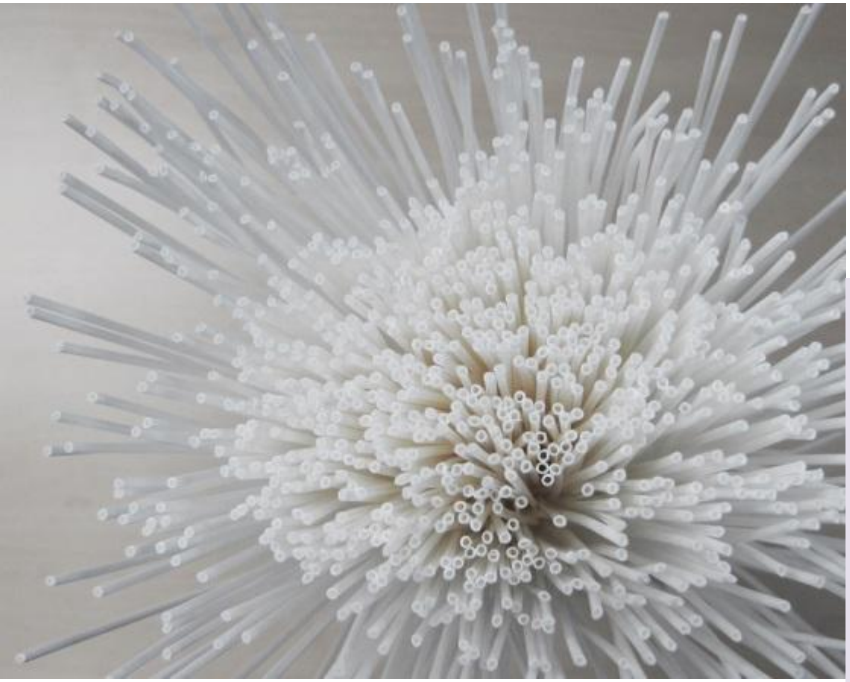
Melt spinning - in which a thermoplastic polymer is melted and extruded through a spinneret, into air, and subsequently cooled.

Dry spinning - in which a polymer is dissolved in an appropriate solvent then extruded through a spinneret into air.

Dry-Jet Wet Spinning - in which a polymer is dissolved in an appropriate solvent then extruded into air and a subsequent coagulant (usually water).

Wet spinning - in which a polymer is dissolved and extruded directly into a coagulant (usually water)

Hollow fiber membranes (Ultrafiltration)

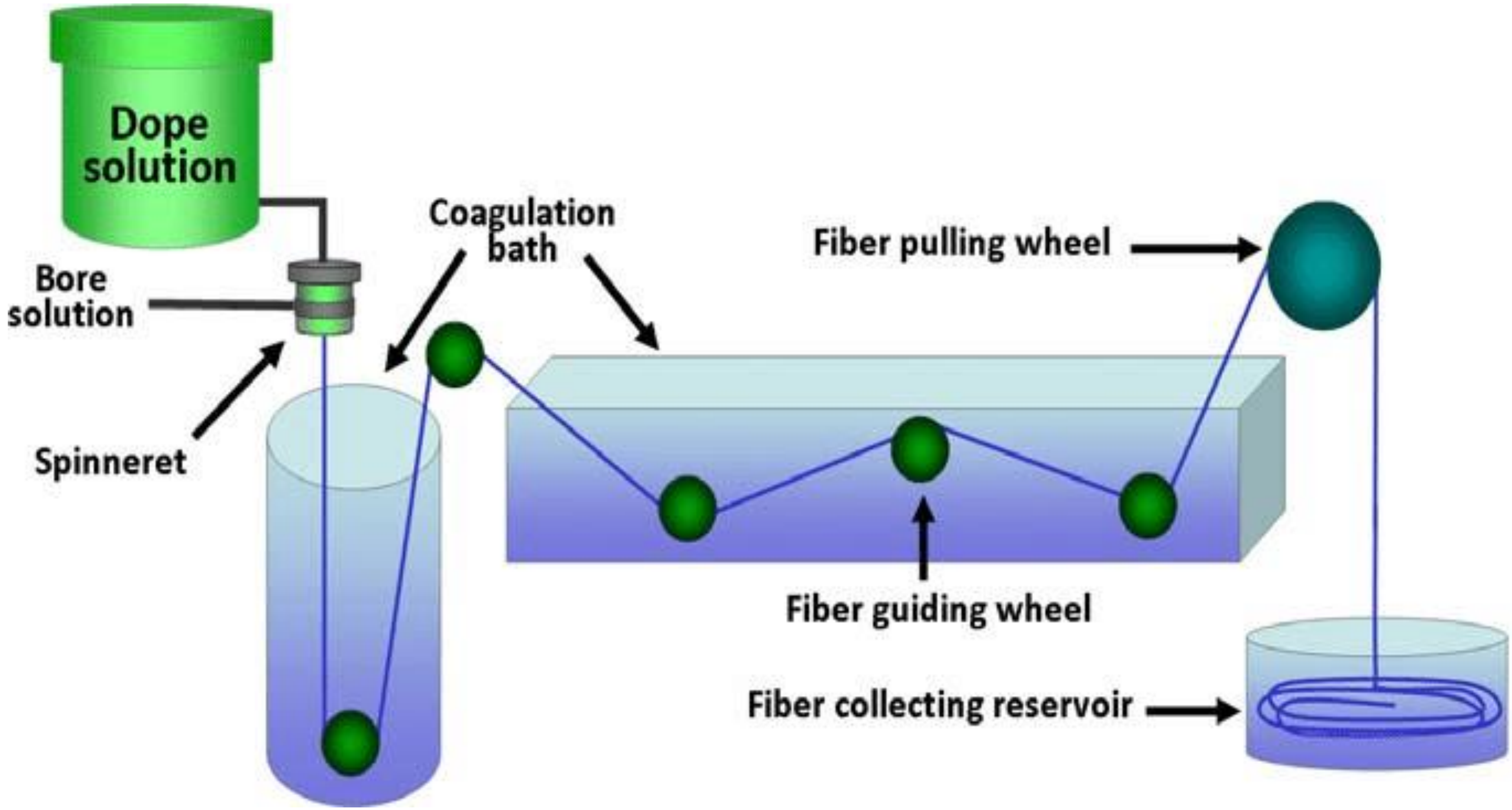


Ultrafiltration HF membrane spinning by phase separation method

Operates without any external pressure or at very low pressure (<20 psi); Removes harmful pathogens (4 to 6 log reductions) and other contaminants like turbidity and colloidal materials from water: Ideal for population having access to treated water

Different polymers used: Polysulfone, Polyethersulfone, Polyacrylonitriles, Polyvinylidene fluoride

HF inner diameter: Vary from 500-600 m, Outer diameter vary from 1000-1200 micron , solute cut-off: ranges of 10-100 Kda & can be tuned



Some of the common polymers used in the production of Hollow Fiber Membranes (HFM) are cellulose acetate, polysulfone, polyethersulfone, and polyvinylidene fluoride.

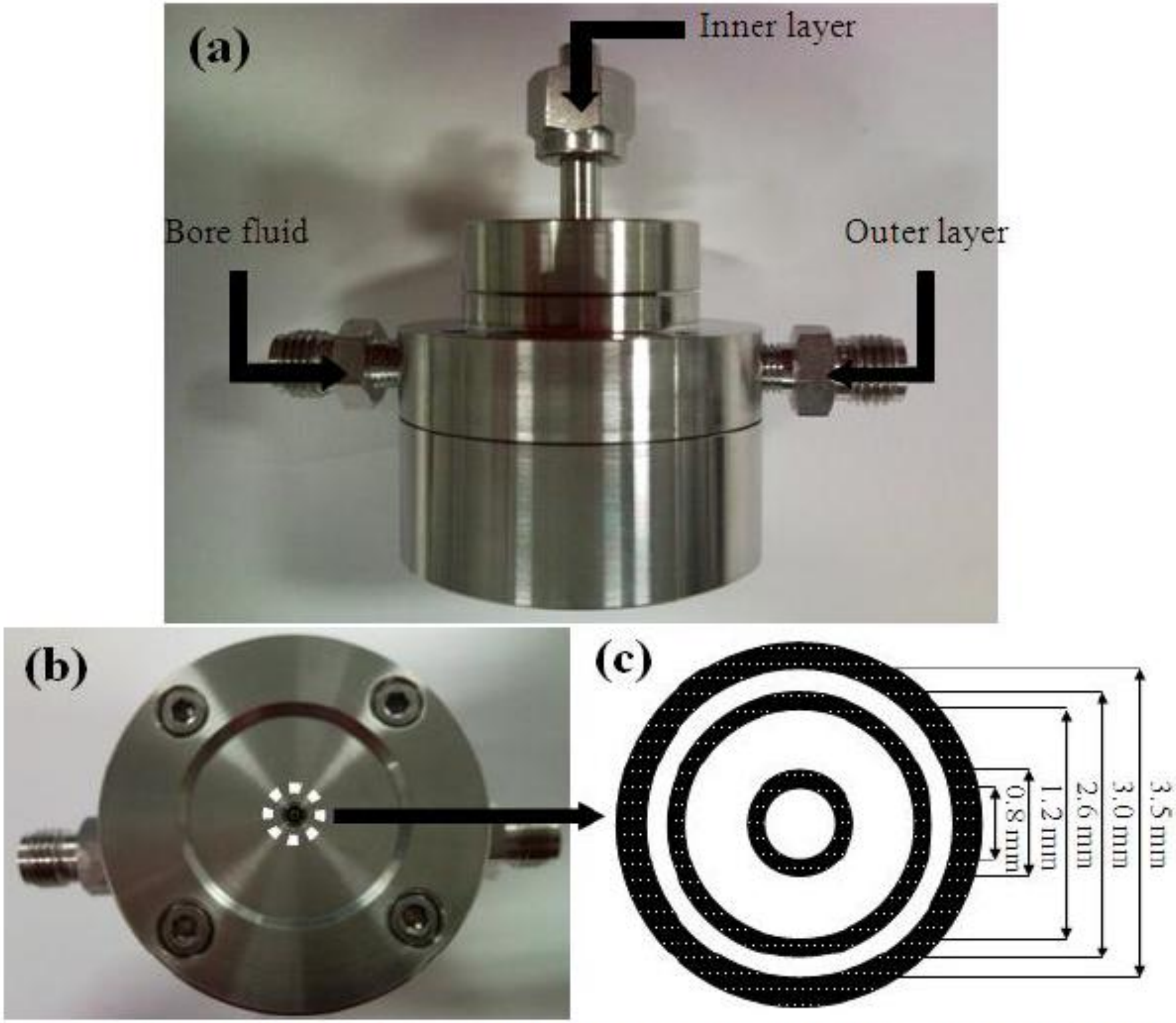


Fig. 2. Photographic images of (a) triple orifice spinneret from side, (b) triple orifice spinneret from bottom, and (c) dimension of the triple orifice spinneret [17].

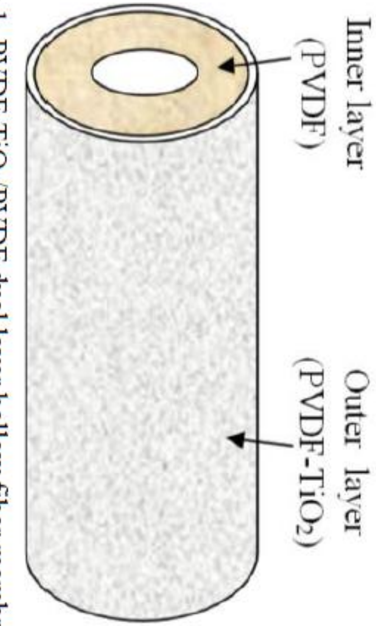


Fig. 1. PVDF-TiO_2/PVDF dual layer hollow fiber membrane.

Int. J. Chem. Eng. Applic., 2015, 6, 289

A spinneret: A device used to extrude a polymer solution or polymer melt to form fibers. Streams of viscous polymer exit via the spinneret into air or liquid leading to a phase inversion which allows the polymer to solidify. The spinneret contains a needle through which the solvent is extruded and an annulus (a ring-shaped object, structure, or region) through which a polymer solution is extruded. As the polymer is extruded through the annulus of the spinneret, it retains a hollow cylindrical shape. As the polymer exits the spinneret, it solidifies into a membrane through a process referred to as phase inversion. The properties of the membrane, such as average pore diameter and membrane thickness can be fine tuned by changing the dimensions of the spinneret, temperature and composition of the polymer and solvent solutions. Extrusion of the polymer and solvent through the spinneret can be accomplished either through the use of gas-extrusion or a metered pump.

Some of the more common polymers used in the production of Hollow Fiber Membranes (HFM) are cellulose acetate, polysulfone, polyethersulfone, and polyvinylidene fluoride.

Hollow Fiber Membrane for Kidney Dialysis:

One of the highly effective uses of Hollow Fiber membranes is in the application of Kidney Dialysis Treatment.

Wastes in the bloodstream are primarily removed through a natural process called diffusion. Diffusion happens when fluids are on both sides of a semi-permeable membrane, like a tea bag. In the dialysis process, the blood cells and proteins are too large to pass through the membrane, so they stay in the body during the treatment. The dialysis process is generally accomplished through one of two membranes:

https://www.outbackwater.com/hollow-fiber-membrane-technology-at-work/

On one side of the membrane is the blood. On the other side of the membrane is a fluid called dialysate, or bath. Wastes from the blood diffuse through the membrane and into the bath. Once used, the bath is to be discarded.

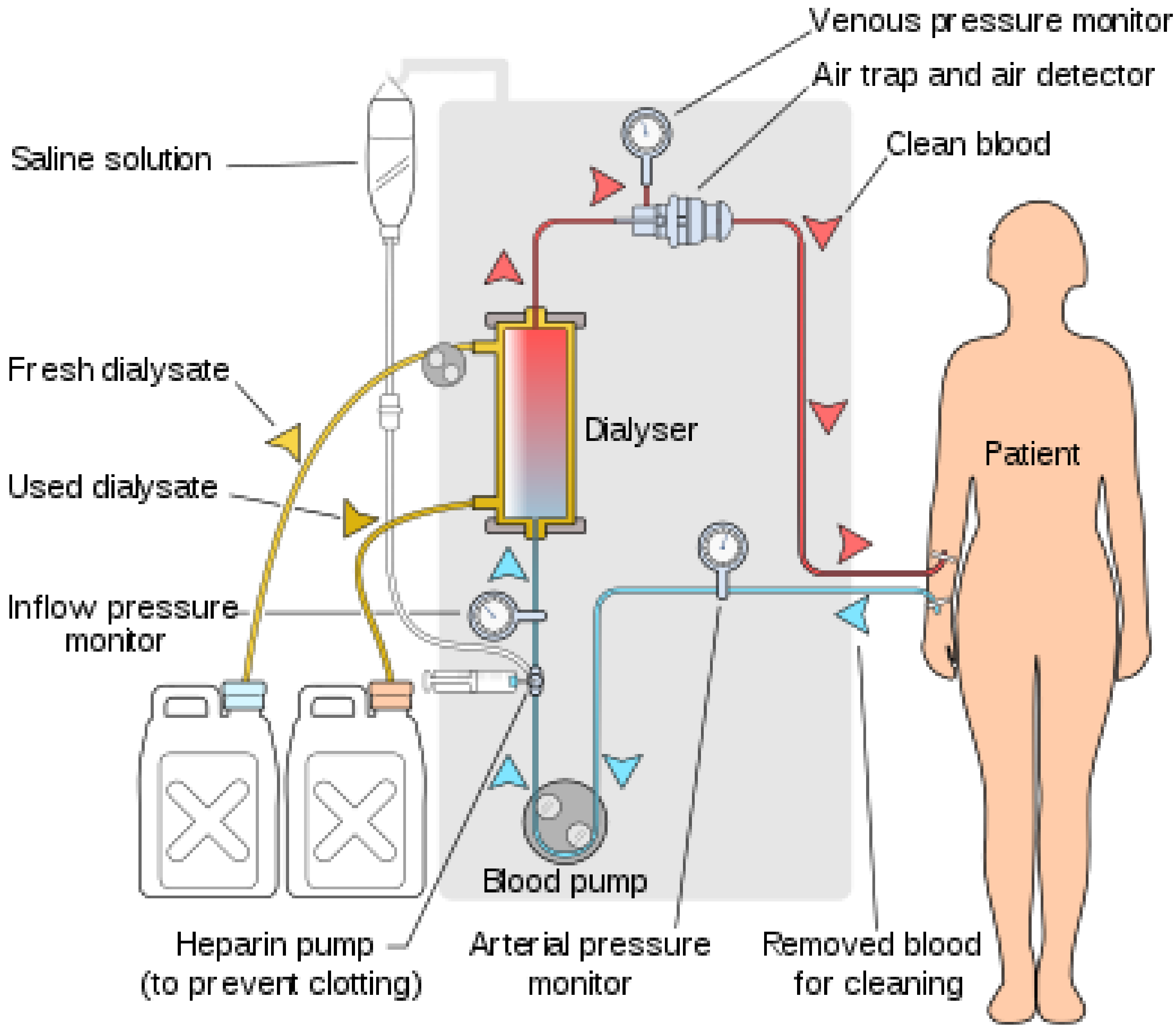
How does dialysis remove only the wastes? The secret is in the bath.

In nature, diffusion goes on until fluids on both sides of a membrane have the same concentration. Referring back to our tea bag example, until the tea is as strong as it can get - which takes time.

In dialysis the process can be speeded up by creating a gradient (pressure), making the fluid on one side of the membrane more concentrated than on the other side.

Blood has high levels of wastes. The gradient forces the wastes from the blood to move across the membrane and into the bath, where the both the bath and the waste are discarded.

https://www.outbackwater.com/hollow-fiber-membrane-technology-at-work/



https://en.wikipedia.org/wiki/Hemodialysis

Unmet Challenges For sustainability

ENVIRONMENTAL IMPACTS

The concentrate (reject salt) still remains the most critical environmental problem, which also affects the cost-effectiveness of desalination. RO plants produce high TDS concentrates (>65,000 mg/L) that may also contain some toxic chemicals used during feedwater pretreatment and post-treatment (cleaning) processes.

Selection of a concentrate management option depends on several factors: concentrate volume and quality, the location of the desalination plant, and the pertinent environmental regulations.

Examples of concentrate management practices include:

Surface water disposal: Disposing of concentrate in tidal rivers and streams, coastal waters such as oceans, estuaries, and bays adjacent to or near the plant. Environmental concerns: Adverse impact on the receiving waters' ecosystems, and the long-term effect on the water quality of coastal aquifers.

Submerged disposal: Concentrate is transported away from the desalination plant via underwater pipes to an estuarine and/or ocean location. Environmental concerns include potential impact of sinking concentrate on benthic marine organisms living on the sea bottom.

Evaporation ponds: Constructed ponds with liners –only viable in areas of warm climates and high evaporation rates. Land-intensive and also cause significant loss of the basic water resource through evaporation.

Land application: For a beneficial use of concentrate, e.g., concentrate can be used to irrigate salt-tolerant crops and grasses such as those used on golf courses.

Brine concentrators: The brine concentrator process uses heat exchangers, deaerators, and vapor compression to convert liquid concentrate into slurry form. It allows recovery of ~95 % of the water as a high-purity distillate with less than 10 mg/L of TDS concentration. The remaining concentrated slurry is reduced to dry solids in a crystallizer to create dry, solid cake, which is easy to handle. Cautionary note: Some chemicals may be present in the dry solid.

Zero liquid discharge (ZLD): The ZLD is promoted as a new technology for concentrate management. The ZLD technique uses an evaporation process to convert a liquid concentrate (brine) into a dry solid. It is a high-energy-intensive technique.

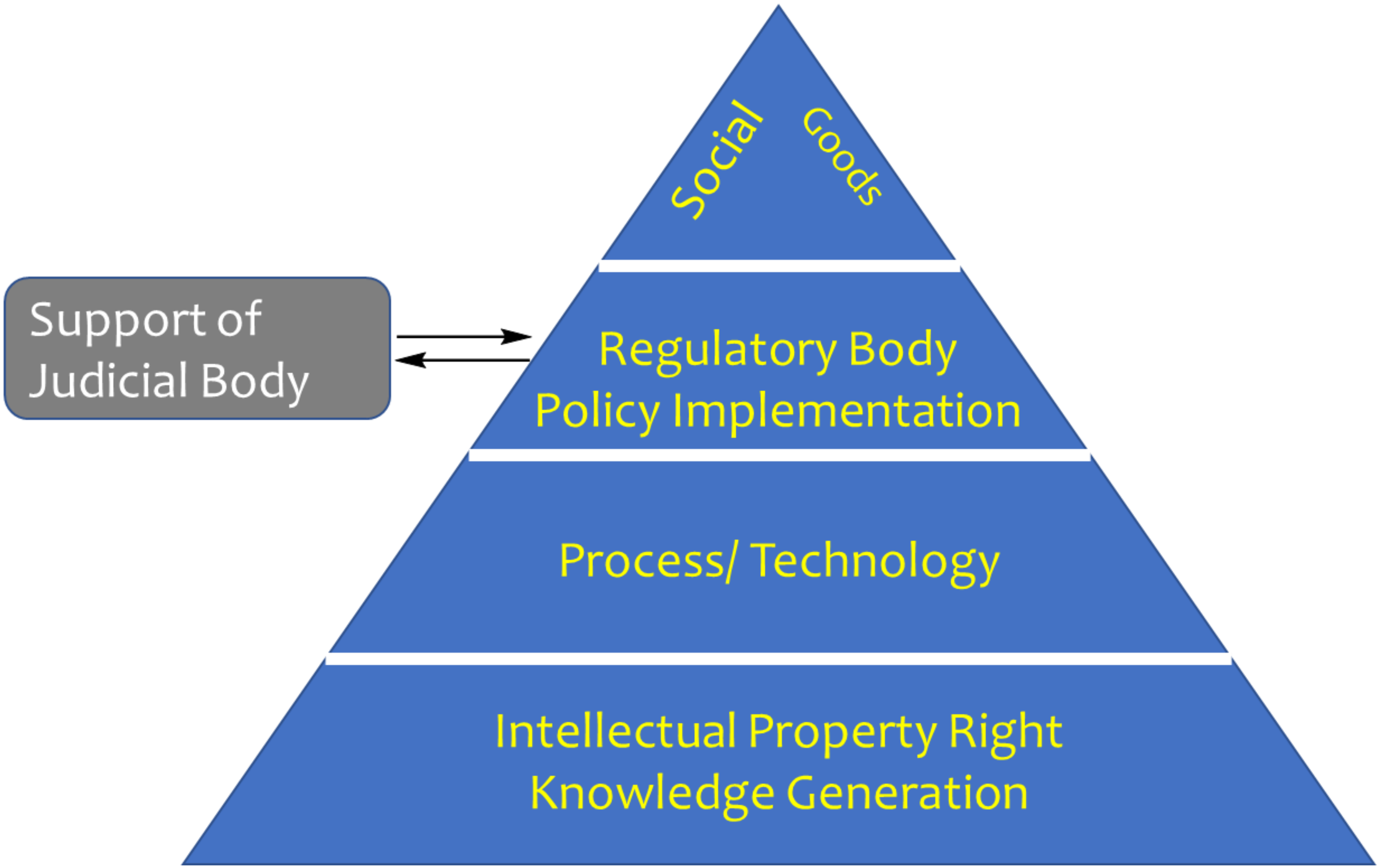
Table 4. Comparison of ZLD Energy Consumption for Various Thermal Technologies[3]

Brine Treatment Technology	Electrical Energy (KWh/m³)	Thermal Energy (kWh/m³)	Total Energy Equivalent* (kWh/m³)	Typical Capacity (m³/day)	Max TDS (mg/L)
MSF	3.68	77.5	38.56	<75,000	250,000
MED	2.22	69.52	33.50	<28,000	250,000
MVC	14.86	0	14.86	<3,000	250,000

*Total Energy Equivalent = Electric Energy + 0.45 x Thermal Energy

https://www.waterworld.com/home/article/14071194/desalination-opportunities-and-challenges

Multi-stage flash distillation (MSF)
Multi-Effect Distillation (MED)
Mechanical Vapour Compression (MVC)

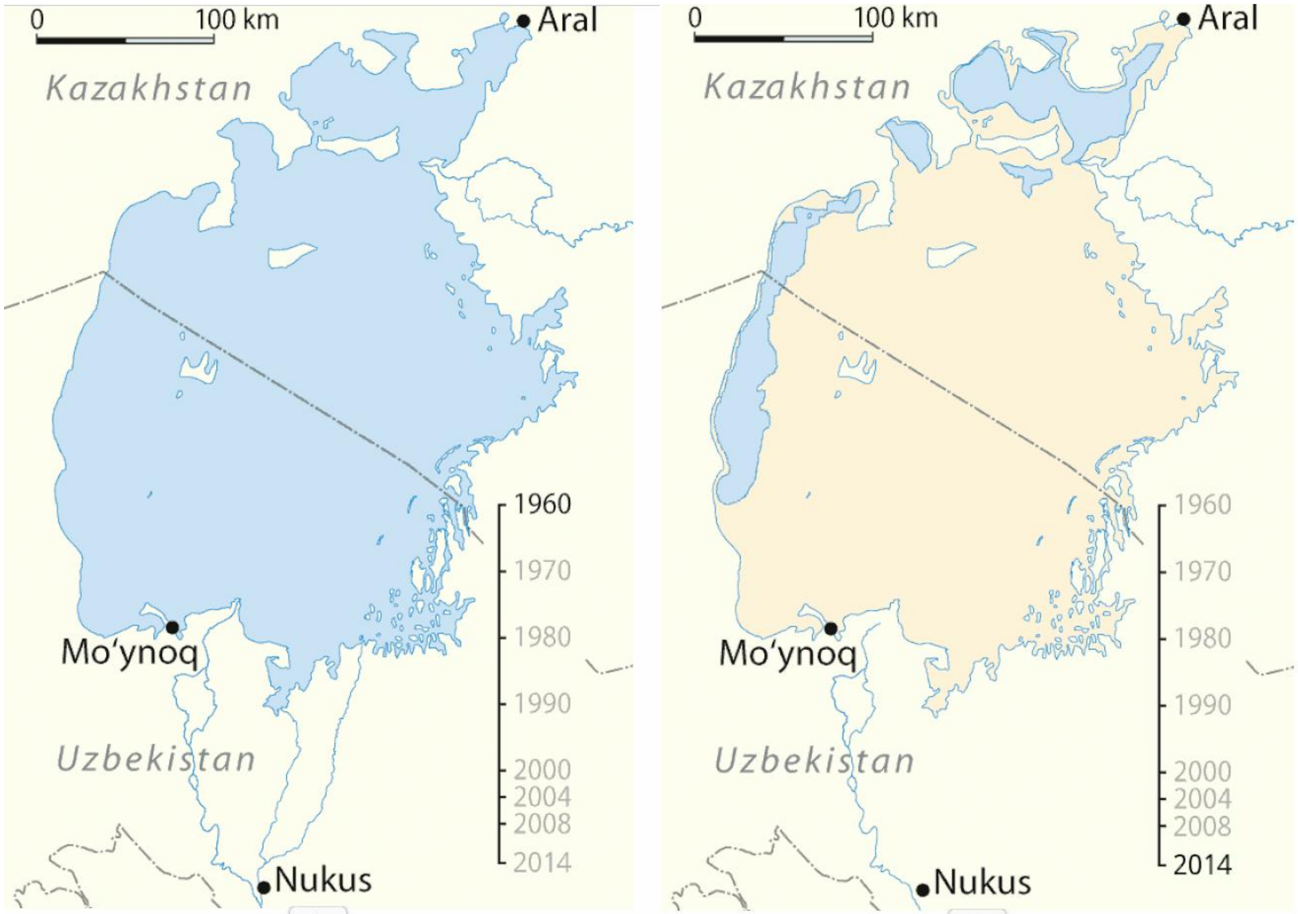

Social Goods
Regulatory Body
Policy Implementation
Process/ Technology
Intellectual Property Right
Knowledge Generation
Support of
Judicial Body

Desiccation of the Aral Sea: **Aral Sea Catastrophe: One of the Worst Ecological Calamities of the Last Century and**
An Example of Misplaced Economic Priorities over Environmental One

The Aral Sea is a lake located east of the Caspian Sea between Uzbekistan and Kazakhstan in Central Asia—is a part of the Turkestan desert, which is the fourth largest desert in the world. Satellite images revealed that the water level has decreased 40-fold in the past five decades.
The lake is divided into two parts: the large Aral in the territory of Uzbekistan and the small Aral in Kazakhstan.

It is produced from a rain shadow effect by Afghanistan's high mountains to the south. Due to the arid and seasonally hot climate, there is extensive evaporation and limited surface waters in general. Summer temperatures can reach 60°C. The water supply to the Aral Sea is mainly from two rivers, the Amu Darya and Syr Darya. In the early 1960s the then-Soviet Union diverted the Amu Darya and Syr Darya Rivers for irrigation of one of the driest parts of Asia to produce rice, melons, cereals, and especially cotton (white gold)—to become a major exporter. They were successful and today Uzbekistan is one of the world's largest exporters of cotton. Unfortunately, this action essentially eliminated any river inflow to the Aral Sea and caused it to disappear almost completely.

Aral Sea, formerly the fourth-largest freshwater lake in the world with an area of 68,000 square kilometres, has transformed into the expanses of the Aralkum Desert that emerged in its place.

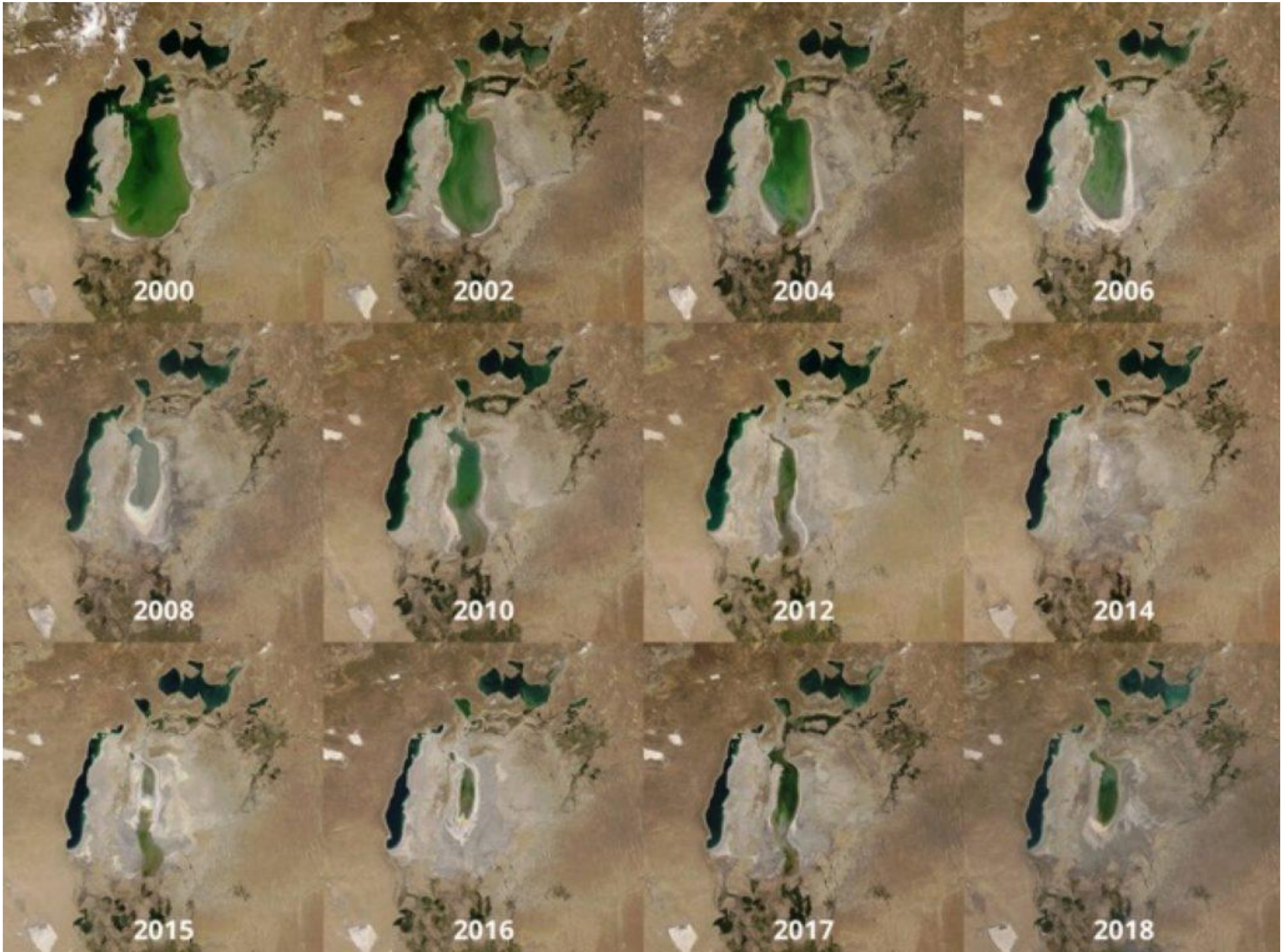


https://adarshbadri.me/politics-society/aral-sea-and-bad-politics/

The United Nations Development Programme called the Aral Sea the "most staggering disaster of the twentieth century" (Grabish 1991). It is a prime example of what unsustainable growth—i.e., economic growth that disregards ecological concerns—can produce.

Besides aquatic species, the Aral Sea used to be a crucial stopover point for millions of migratory birds travelling along the Central Asian flyway. As the sea shrank, wetland habitats vanished, forcing birds to alter their migration patterns.

Aral Sea Transformation



Impact on the Aral Basin Due to Economic Policies of **the Soviet Union.**

The Collectivisation of Agricultural Land in the Soviet Union.

Human Impact of the Aral Sea Crisis.

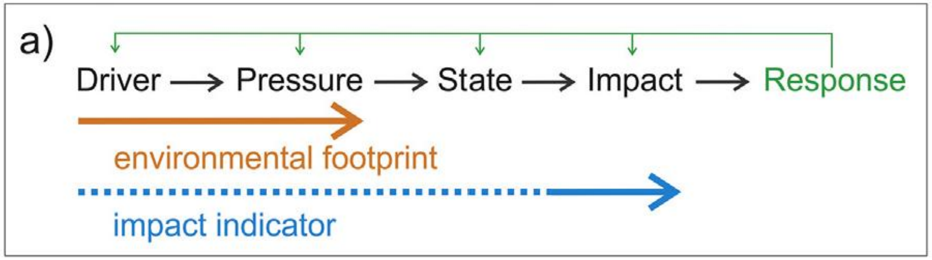
Salination of Water in the Aral Sea; Health Crisis in the Aral Sea Basin; the varieties of fish in the region have also reached extinction (Micklin and Aladin 2008). The 20 fish species in the sea, which were crucial for the region's economy and nutrition, have perished.

Societies find it difficult to balance between the economy and ecology. In economics, we are taught "opportunity cost"—the value of gaining something at the cost of something else. It is a trade-off.

The link between Environmental Footprint Indicators and Planetary Boundary:

The planetary boundary (PB) concept, introduced in 2009, aimed to define the environmental limits within which humanity can safely operate. Integrating different footprints into a coherent framework is important as this helps in a comprehensive understanding of environmental issues, policy formulation and assessment of trade-offs between different environmental concerns. [Science of the Total Environment 693 (2019) 133642]

Environmental Footprint Assessment (EFA) and **Life Cycle Assessment** (LCA) are both based upon life cycle thinking but differ in aim and approach. **Environmental footprints** are usages of resources and emissions oriented, combined referred to as pressure oriented, whereas **LCA is impact-oriented**. Pressure indicators are different from impact indicators, as they inform users about the pressure human activities place on ecosystems (e.g., the land used to produce a crop) rather than on the potential consequences (impact) due to such pressure.



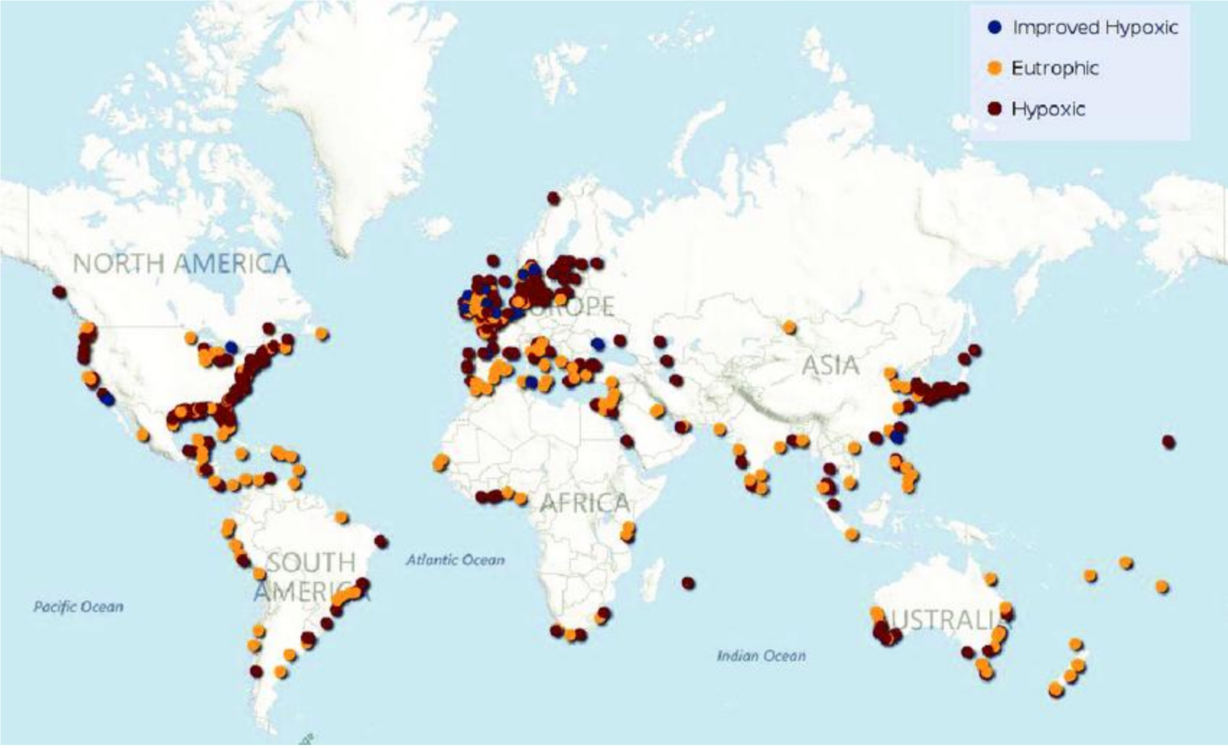
Rockstrom et al. (2009) and Steffen et al. (2015) identified nine critical processes that regulate the Earth system functioning.

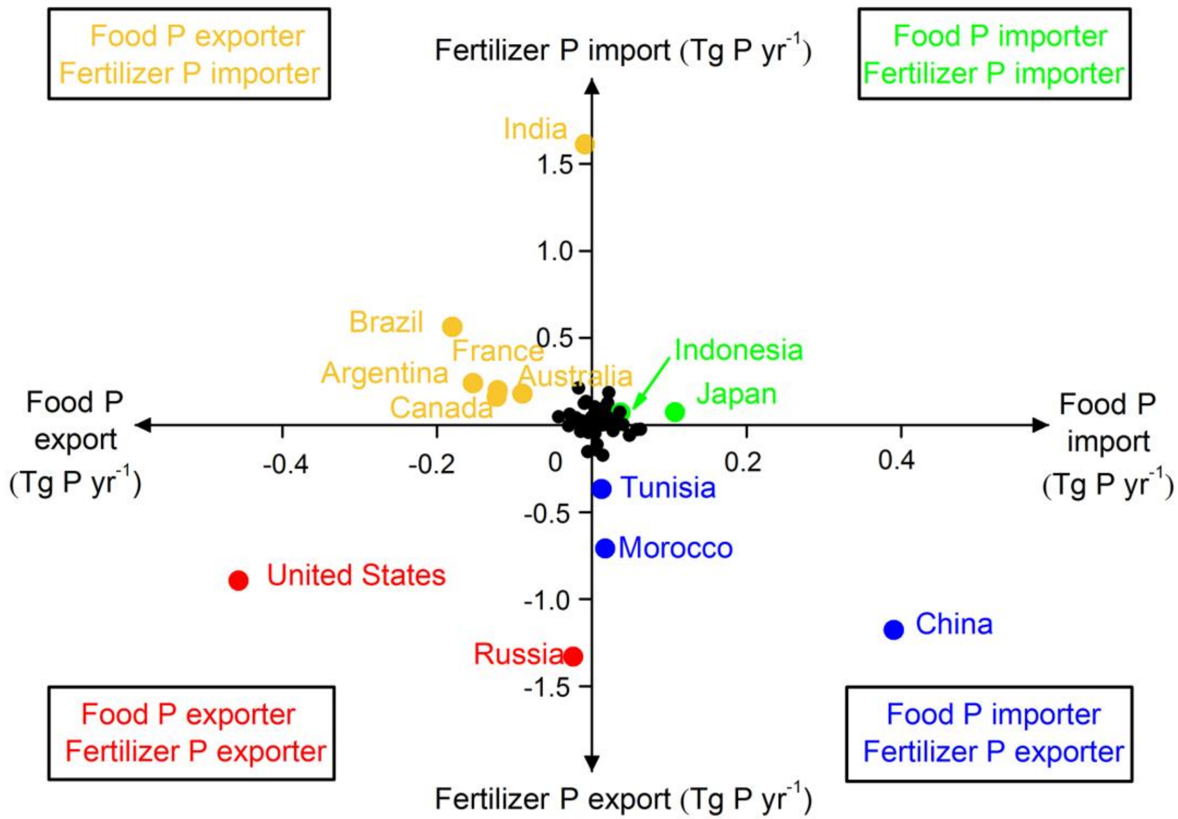
The average N:P ratio in growing plant tissue is approximately 11.8:1 (desirable).
Currently, the global N:P loss ratio is approximately 11.2:1 (138 vs 12 Tg y^{-1})

Eutrophication

A process of pollution, which occurs when a lake or stream becomes over-rich in plant nutrients; as a consequence, it becomes overgrown in algae and other aquatic plants. The plants die and decompose and in the process utilize the oxygen of the body. The bloom also cuts off the sunlight. Nitrate fertilizers which drain from the fields, nutrients from animal wastes and human sewage are the primary causes of eutrophication

Vegetation relies on photosynthesis for energy; sunlight can't penetrate the ocean depths, so plants can't grow in deeper waters. However, shallow coastal waters are a different story. Many varieties of sea vegetation thrive to depths of about 600 feet (183 meters) in the so-called "euphotic zone."

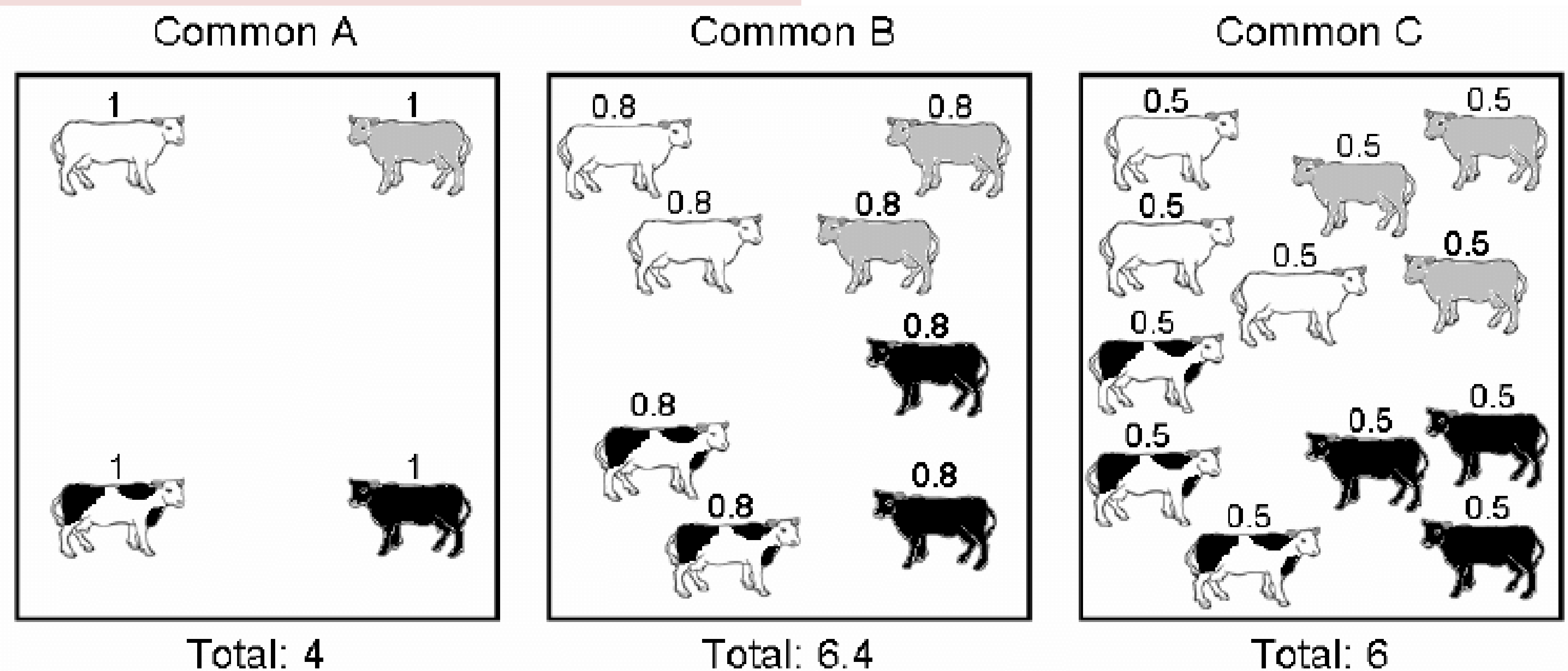


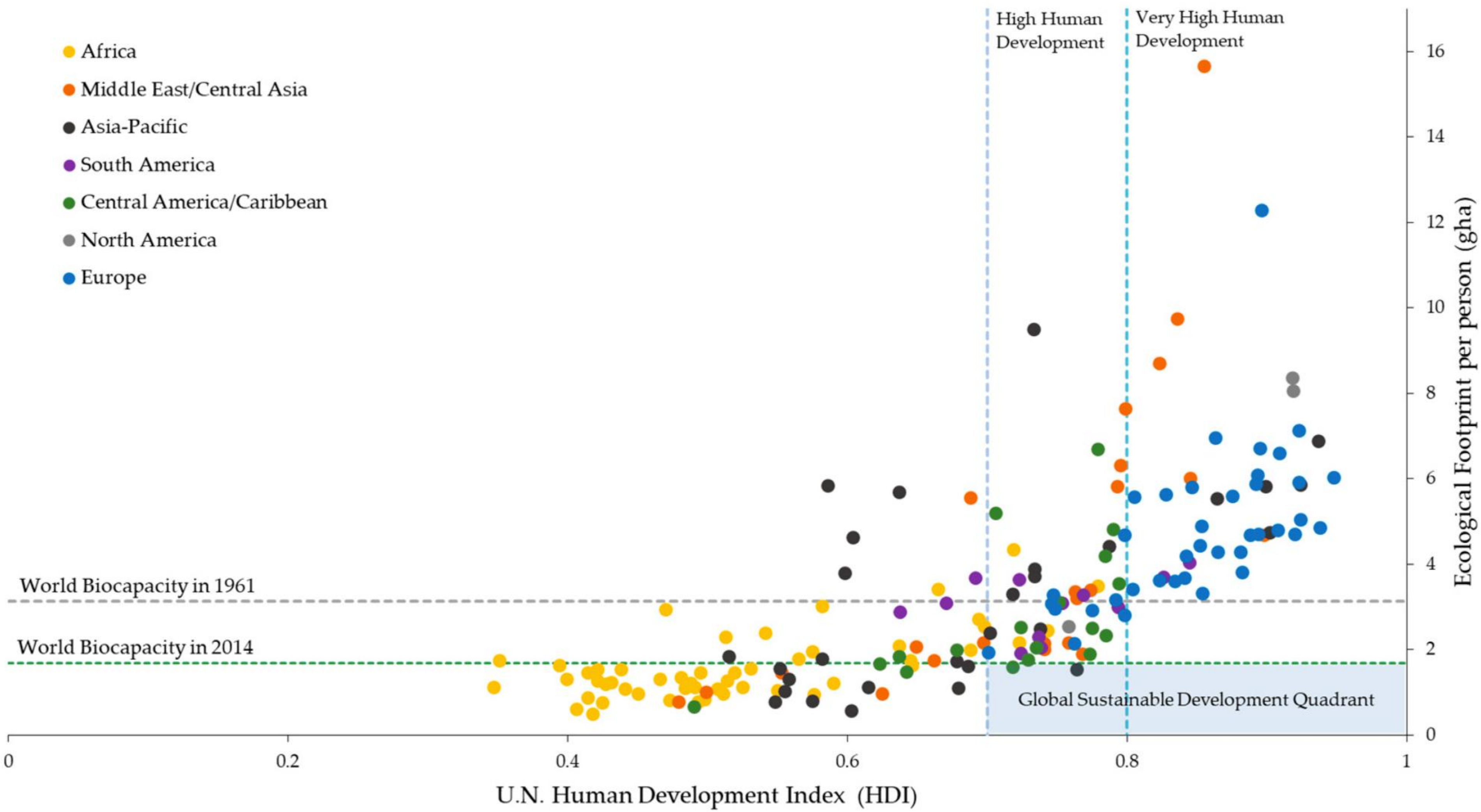


Groupings of the countries based on whether they import or export P through their international trade in food and fertilizer [Earth Syst. Sci. Data, 2018, 10, 1–18; www.earth-syst-sci-data.net/10/1/2018/]

An example of the tragedy of the commons for a pasture that is used by four herdsmen (who have differently coloured cattle). When each herdsman put only one cow on the commons (Common A), the productivity of each cow is 1 (e.g., 1 litre of milk). When the herdsmen introduce more cattle (Common B), the production per animal is reduced due to increased density but the total production is higher. When the carrying capacity is approached (Common C), the total productivity is also reduced. Each individual herdsman will, however, gain nothing from reducing his stock unless other herdsmen do the same.

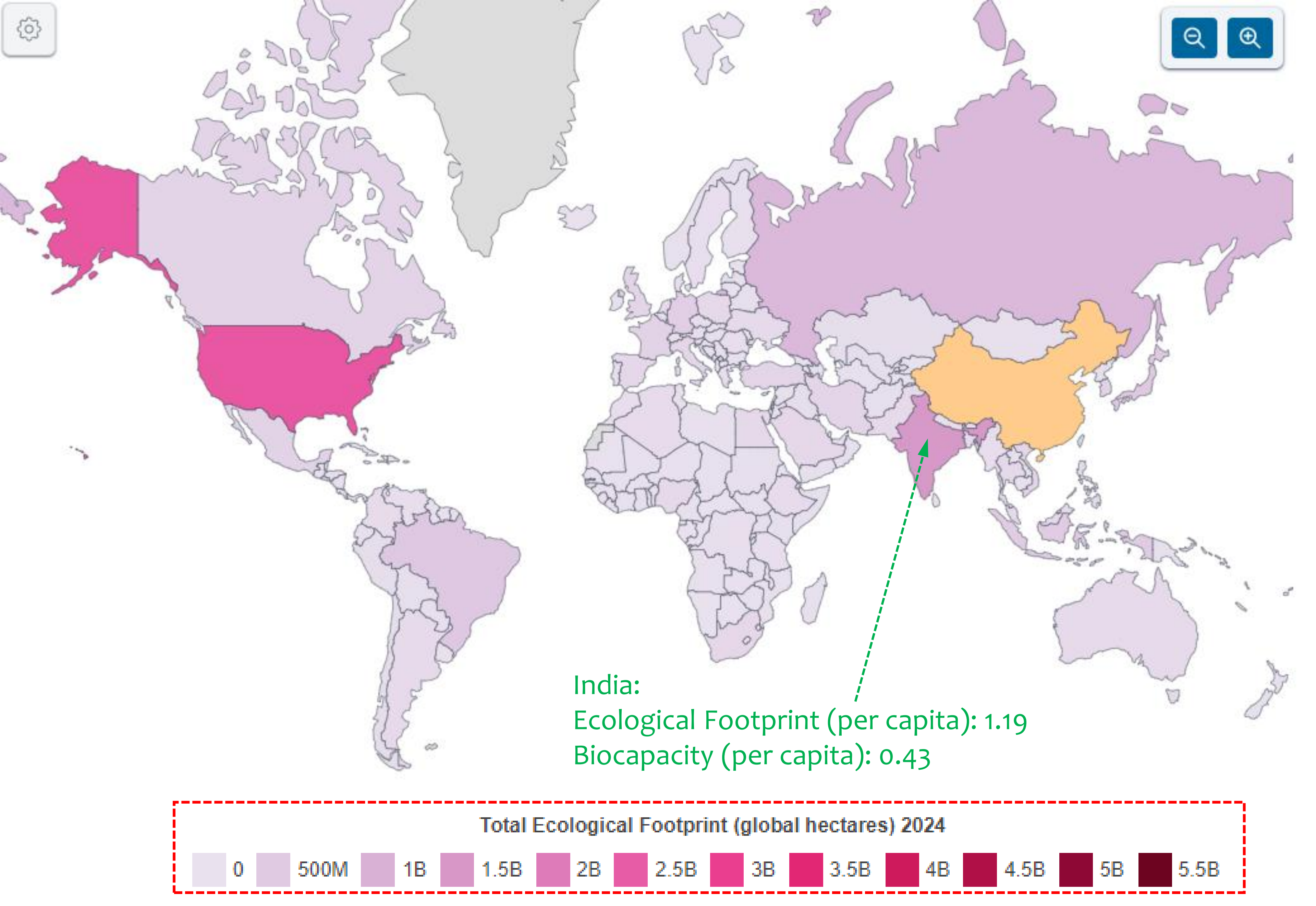
Thesis by Dr. Niklas Hanson, Dept Plant and Env. Sci. University of Gothenburg, Sweden



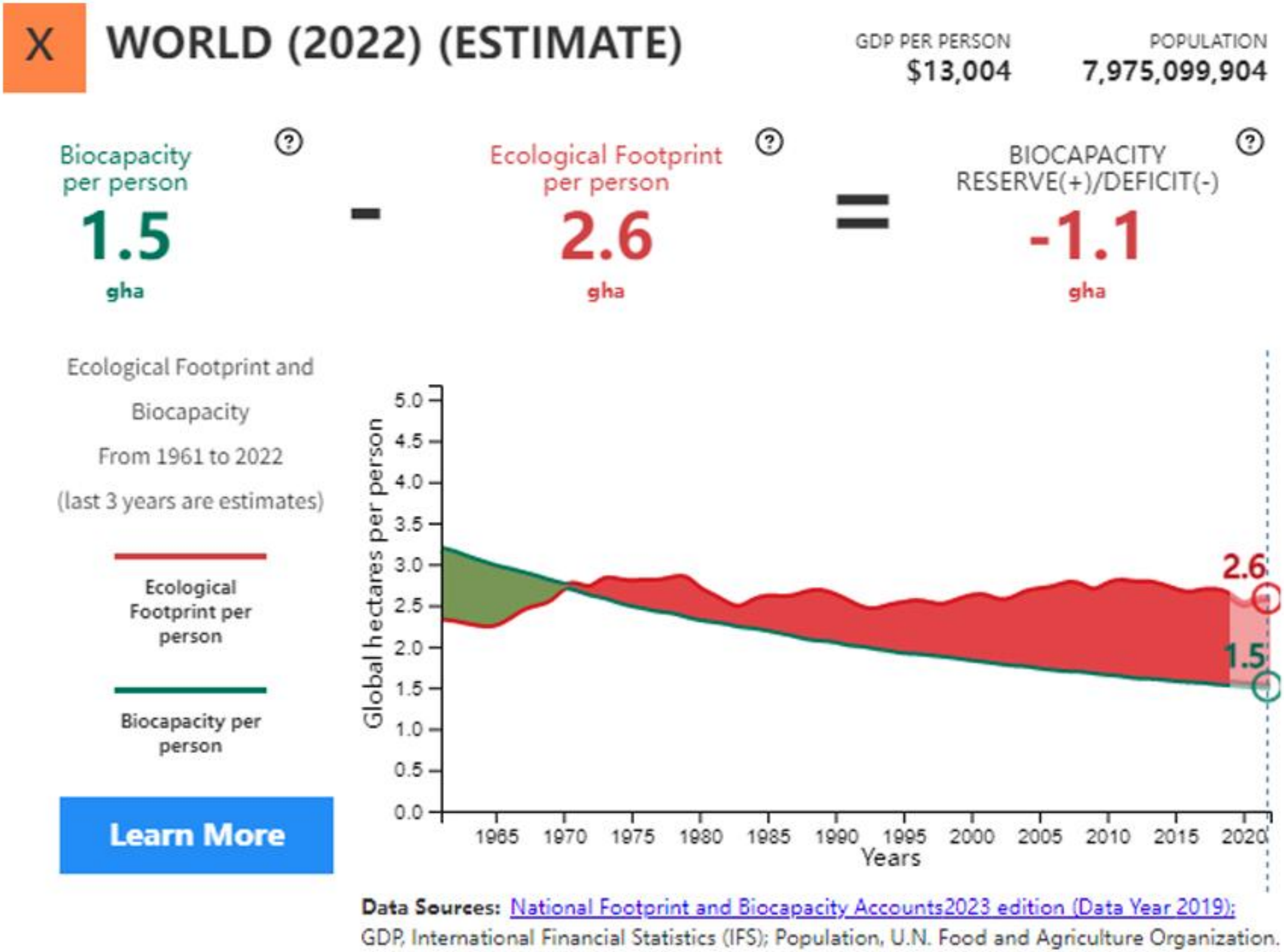


Ecological Footprint in relation to the Human Development Index (HDI) of all countries, grouped by region. The shaded blue box represents the Global Sustainable Development Quadrant, where countries have high levels of human development and globally sustainable resource demands.

Resources 2018, 7(3), 58

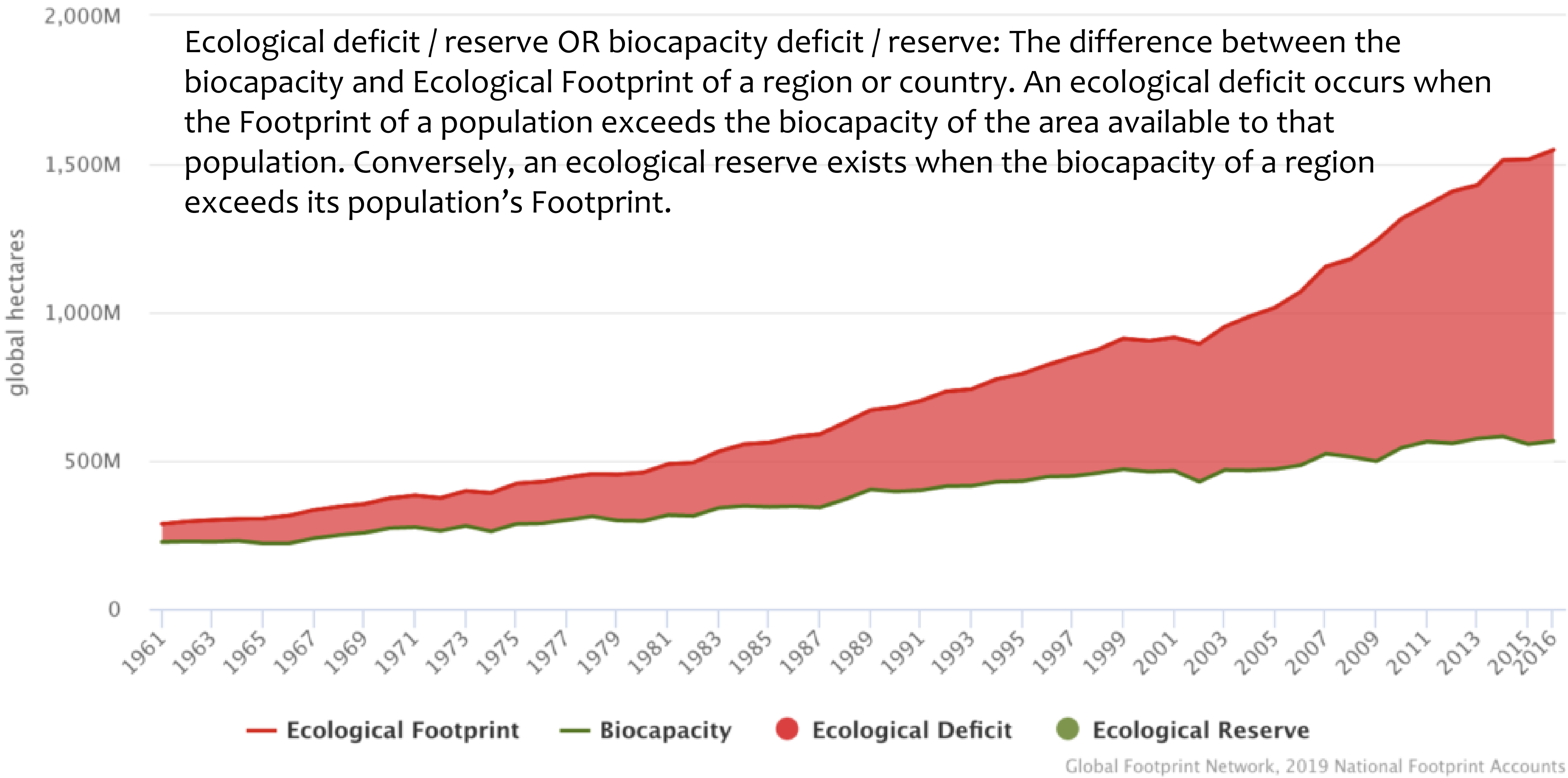


https://worldpopulationreview.com/country-rankings/ecological-footprint-by-country#google_vignette



Humanity's Ecological Footprint and the planet's biocapacity in global hectares per person from 1961 to 2022 (2023 edition). data.footprintnetwork.org

India

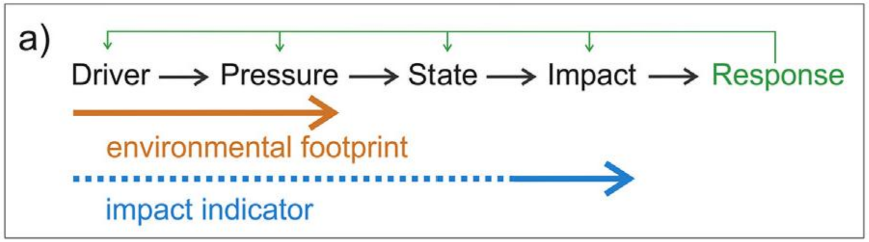


Ecological deficit / reserve OR biocapacity deficit / reserve: The difference between the biocapacity and Ecological Footprint of a region or country. An ecological deficit occurs when the Footprint of a population exceeds the biocapacity of the area available to that population. Conversely, an ecological reserve exists when the biocapacity of a region exceeds its population's Footprint.

The link between Environmental Footprint Indicators and Planetary Boundary:

The planetary boundary (PB) concept, introduced in 2009, aimed to define the environmental limits within which humanity can safely operate. Integrating different footprints into a coherent framework is important as this helps in a comprehensive understanding of environmental issues, policy formulation and assessment of trade-offs between different environmental concerns. Such a relation is linked to the assessment of environmental sustainability. [Science of the Total Environment 693 (2019) 133642]

Environmental Footprint Assessment (EFA) and Life Cycle Assessment (LCA) are both based upon life cycle thinking but differ in aim and approach. Environmental footprints are usages of resources and emissions oriented, combined (EFA) referred to as pressure oriented, whereas LCA is impact oriented. Pressure indicators are different from impact indicators, as they inform users about the pressure human activities place on ecosystems (e.g., the land used to produce a crop) rather than on the potential consequences (impact) due to such pressure.



Rockstrom et al. (2009) and Steffen et al. (2015) identified nine critical processes that regulate the Earth system functioning.

PB in 2015: The nine boundaries humanity must respect to keep the planet habitable

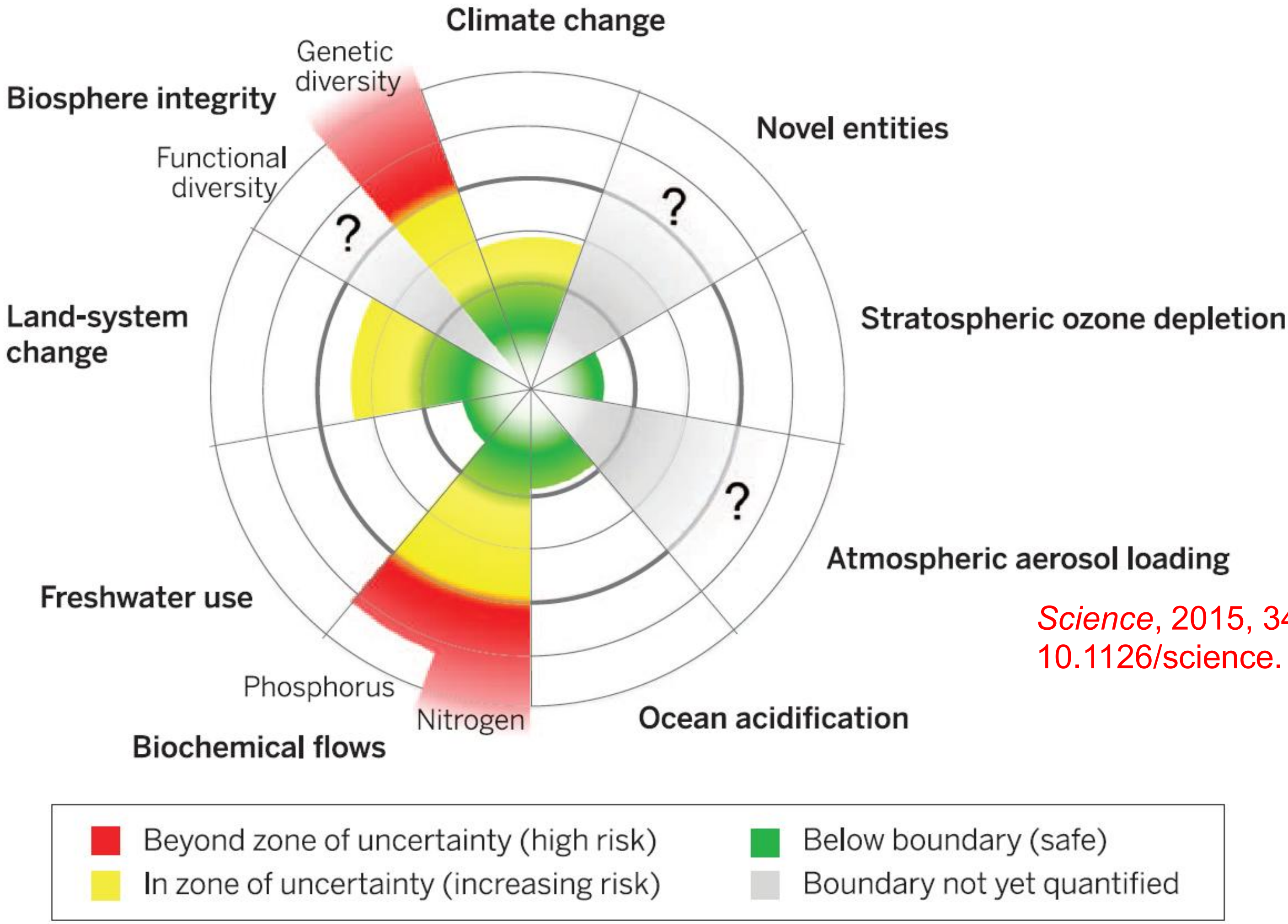
Since its publication in 2009, the concept of planetary boundaries has been highly influential in generating academic debate and in shaping research projects and policy recommendations worldwide. [Safe operating space for humanity; Nature2009, 461(7263):472–75].

Criticism: Many scientific debates addressed specific boundaries and the threshold values that were advanced in 2009—especially the boundary value for freshwater consumption, phosphorus and nitrogen. There have also been several attempts to fill gaps left by the 2009 framework, especially in relation to boundaries for which no clear safe operating space was suggested, such as chemical pollution.

The other **criticism** includes the under-representation of marine systems in the planetary boundaries framework. They hence suggested expanding the scope of the land-system boundary to include the seafloor as an earth surface change boundary. [Annu. Rev. Environ. Resour. 2020. 45:497–521]

Six years after the original publication, an update of the planetary boundaries framework was published in 2015 and this emphasized the dynamic relationships between planetary boundaries.

The planetary boundary itself lies at the intersection of the green and yellow zones. The control variables have been normalized for the zone of uncertainty; the center of the figure, therefore, does not represent values of 0 for the control variables. Climate change: [atmospheric CO_2]

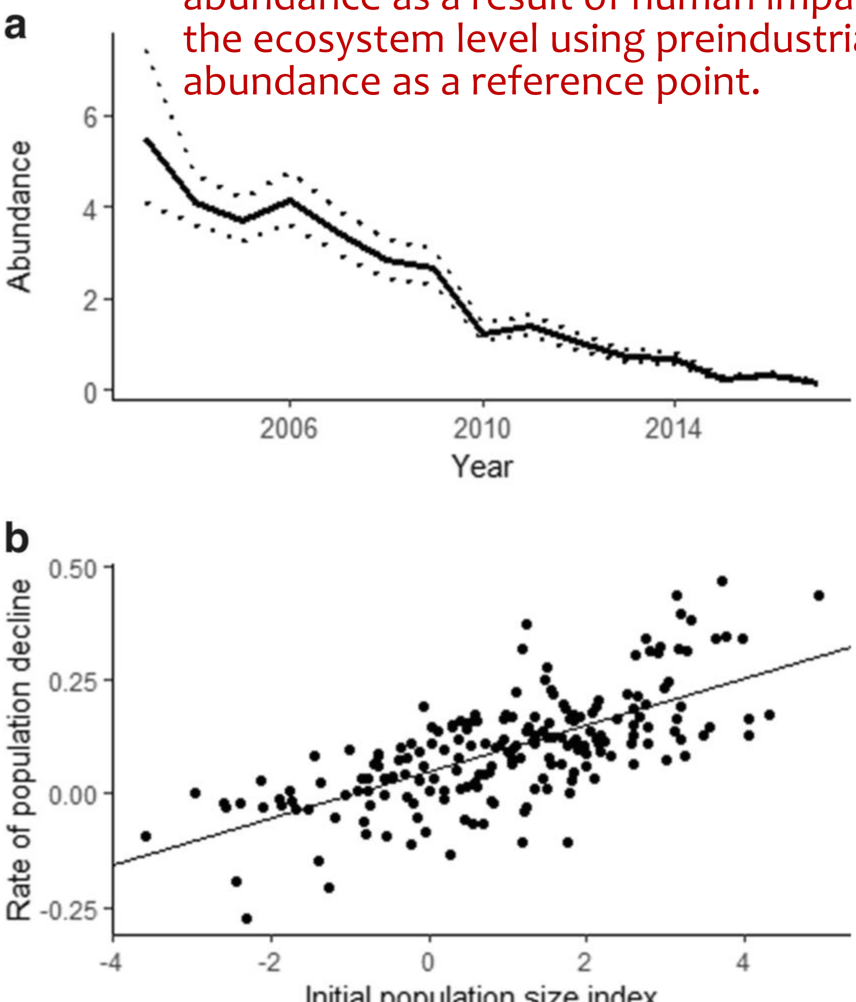


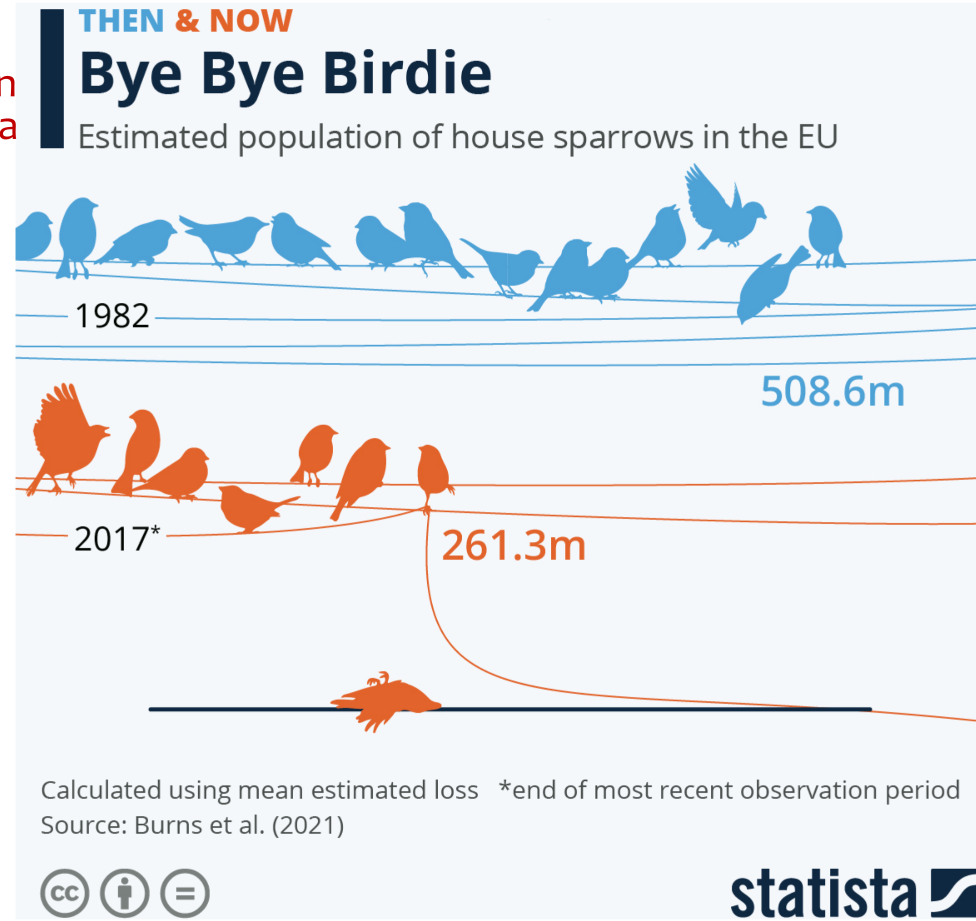
Science, 2015, 347 (6223), 1259855. • DOI: 10.1126/science. 1259855

Processes for which global-level boundaries cannot yet be quantified: are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity

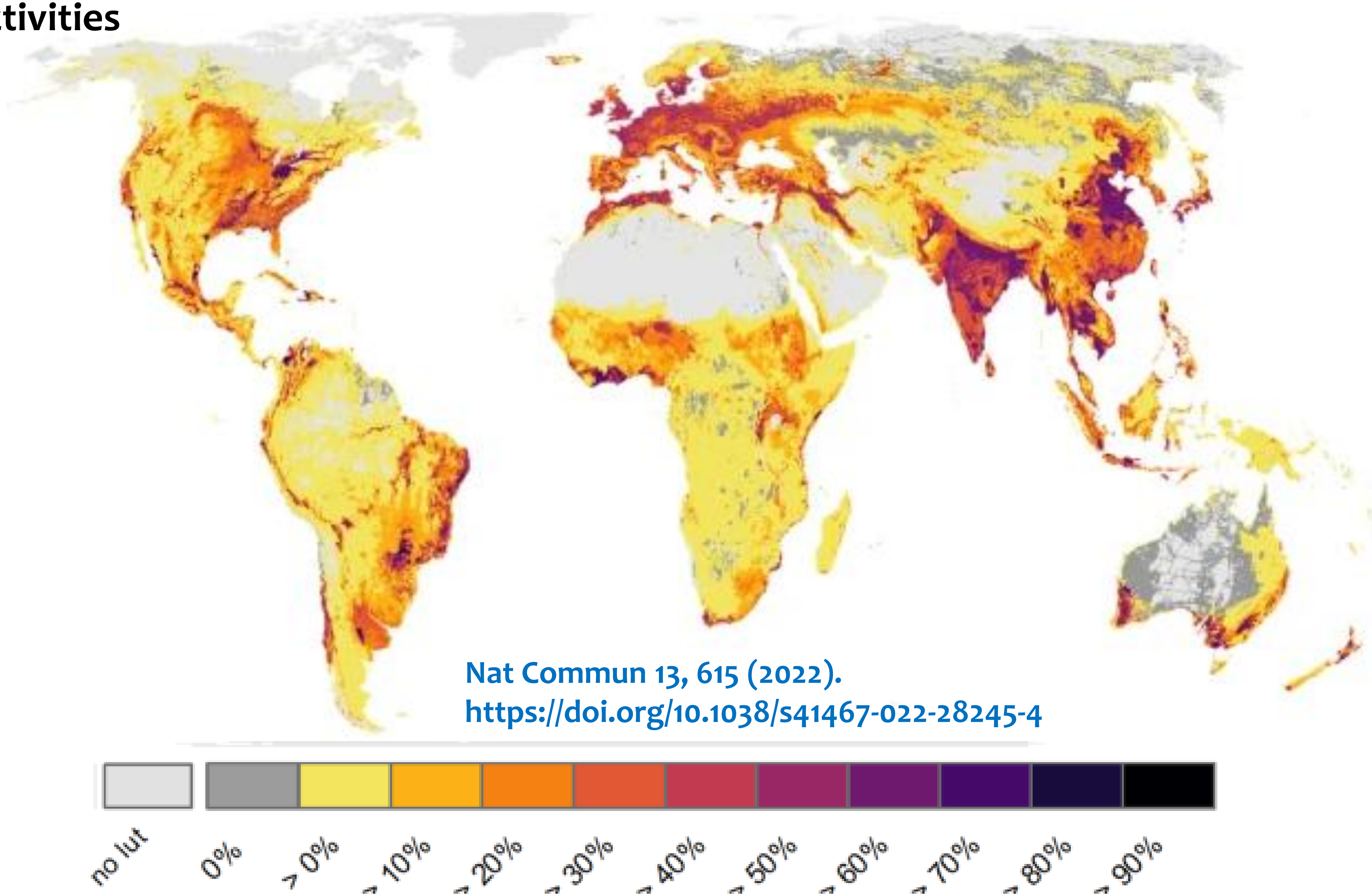
A total of 182 bird species are believed to have become extinct since 1500—19 species were lost during 1975-2000 and four more are known or suspected to have gone extinct since 2000. The rate of extinctions is increasing, principally as a result of extensive and expanding habitat destruction.

Biodiversity Intactness Index (BII):
Assessment of change in population abundance as a result of human impacts in the ecosystem level using preindustrial era abundance as a reference point.



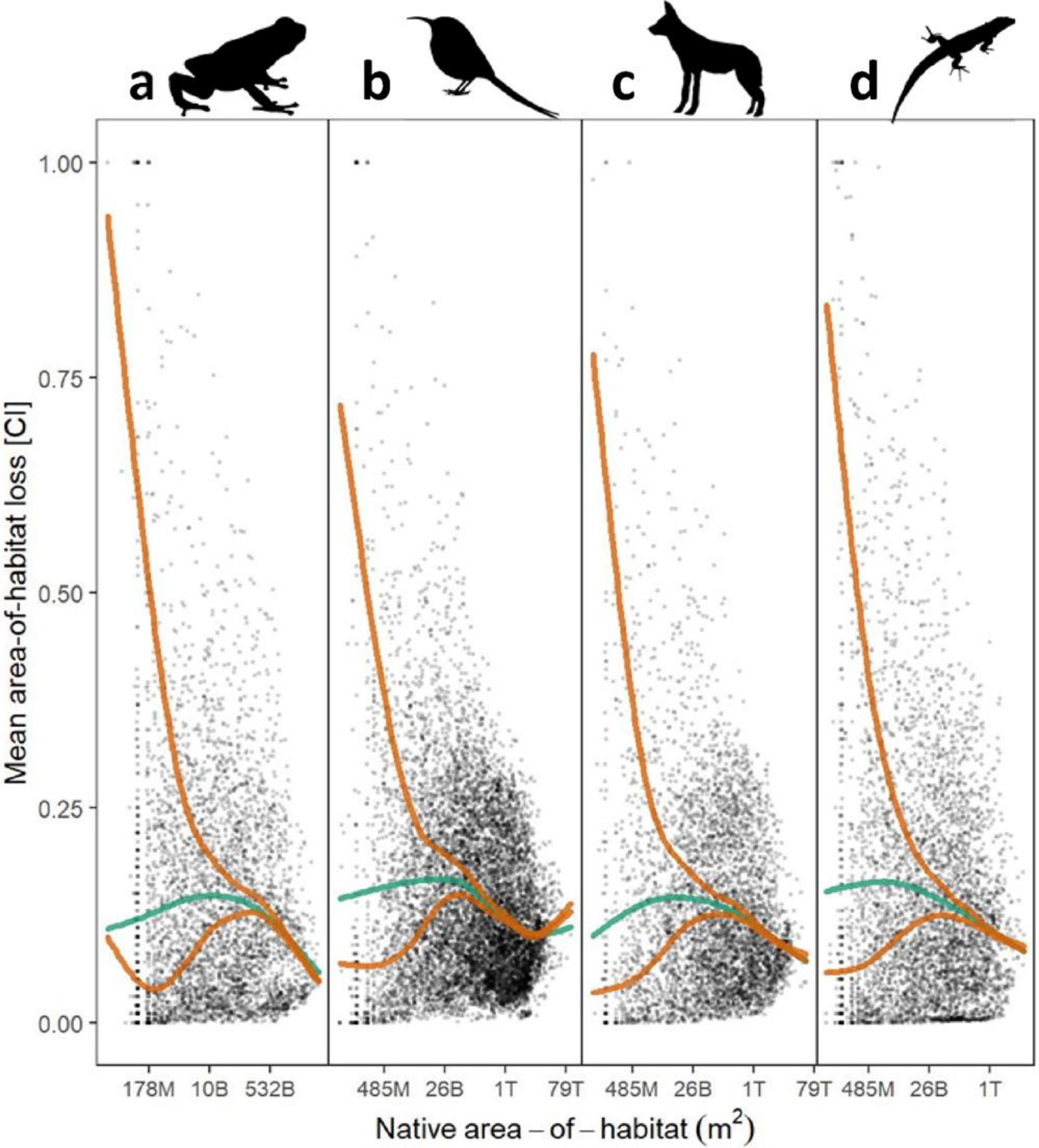


Loss of terrestrial vertebrate species richness in response to current land-use activities



Nat Commun 13, 615 (2022).
https://doi.org/10.1038/s41467-022-28245-4

Land-use has transformed ecosystems over three quarters of the terrestrial surface, with massive repercussions on biodiversity.

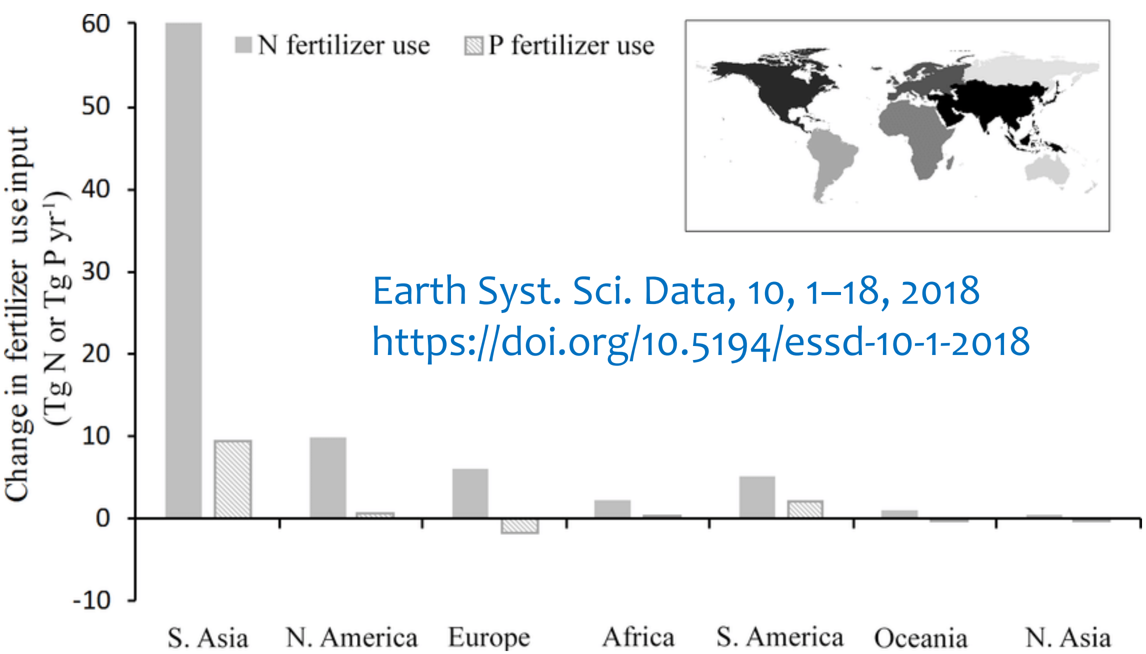


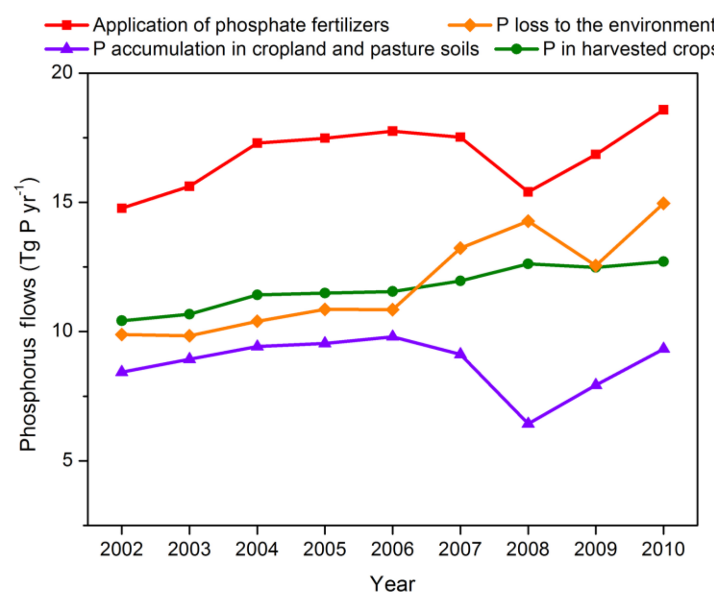
Nat Commun 13, 615 (2022). https://doi.org/10.1038/s41467-022-28245-4

The loss of ~15% of terrestrial vertebrate species from the average 5 × 5 arcmin-landscape outside remaining wilderness areas and ~14% of their average native area-of-habitat, with a risk of global extinction for 556 individual species with substantial (~25%) biodiversity loss.

Biogeochemical flows: linkage between phosphorus and nitrogen boundaries

The average N:P ratio in growing plant tissue is approximately 11.8:1. We consider that an application rate of N and P in fertilizers somewhat nearer the ratio that the crop takes up would be desirable. Using this approach would require the ratio of losses of N and P to the environment via leaching and emissions to the atmosphere to be equivalent to the N:P input ratio. Currently, the global N:P loss ratio is approximately 11.2:1 (138 vs 12 Tg y^{-1}), thus being close to 11.8:1. An N:P ratio of 11.8 for the N to P inputs based on crop uptake could potentially lead to an overloading of aquatic systems with P relative to N, since the typical aquatic N:P mass ratio is near 14. The current loadings of P and N exceed environmental limits and thus are transgressing our proposed planetary boundaries.



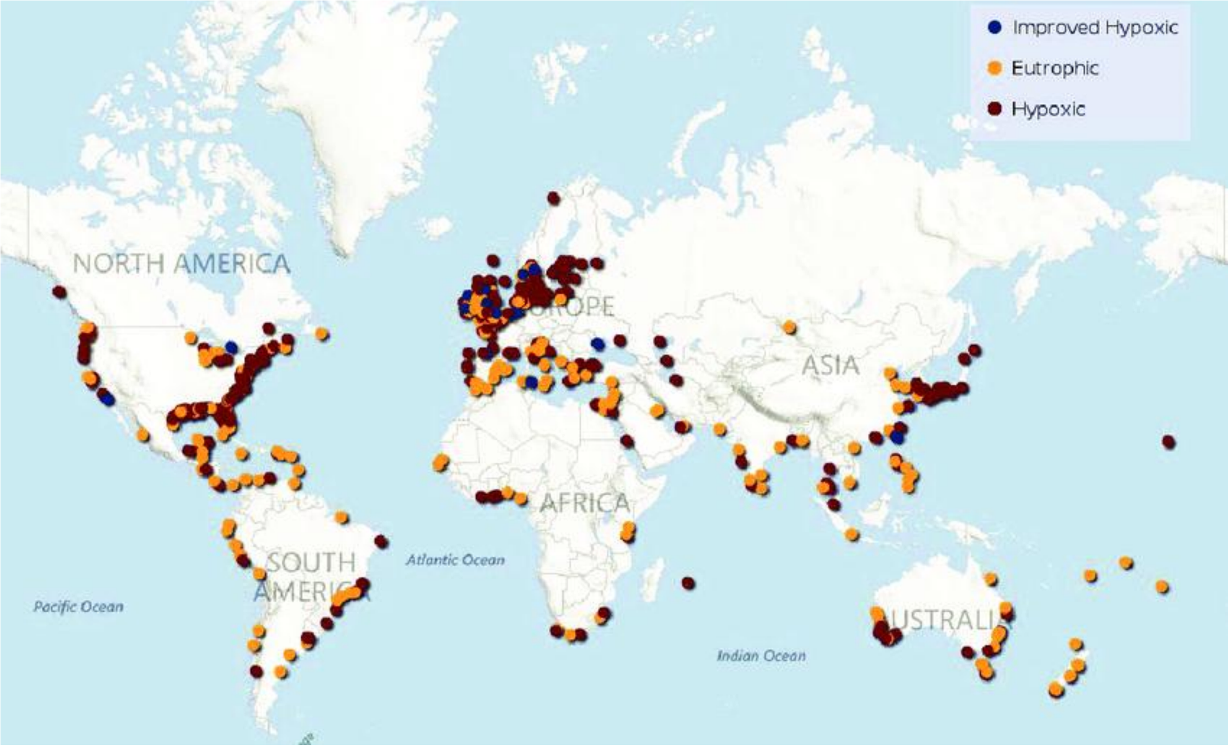


Earth Syst. Sci. Data, 10, 1–18, 2018
https://doi.org/10.5194/essd-10-1-2018

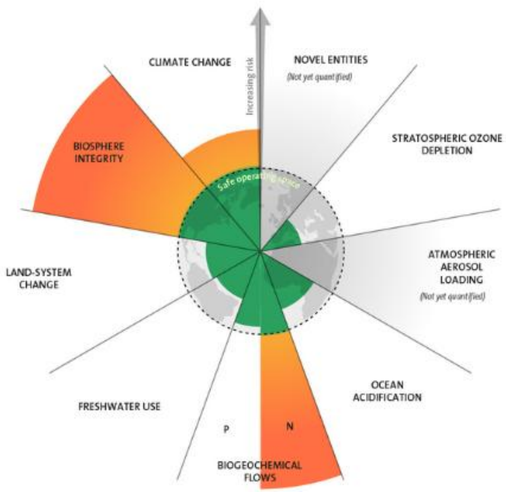
Eutrophication

A process of pollution, which occurs when a lake or stream becomes over-rich in plant nutrients; as a consequence, it becomes overgrown in algae and other aquatic plants. The plants die and decompose and in the process utilize the oxygen of the body. The bloom also cuts off the sunlight. Nitrate fertilizers which drain from the fields, nutrients from animal wastes and human sewage are the primary causes of eutrophication

Vegetation relies on photosynthesis for energy; sunlight can't penetrate the ocean depths, so plants can't grow in deeper waters. However, shallow coastal waters are a different story. Many varieties of sea vegetation thrive to depths of about 600 feet (183 meters) in the so-called "euphotic zone."

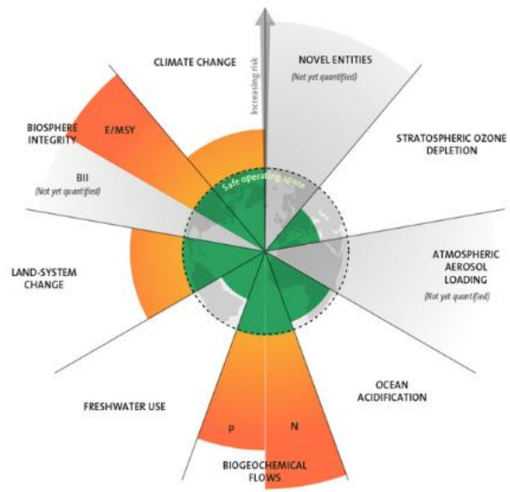


2009



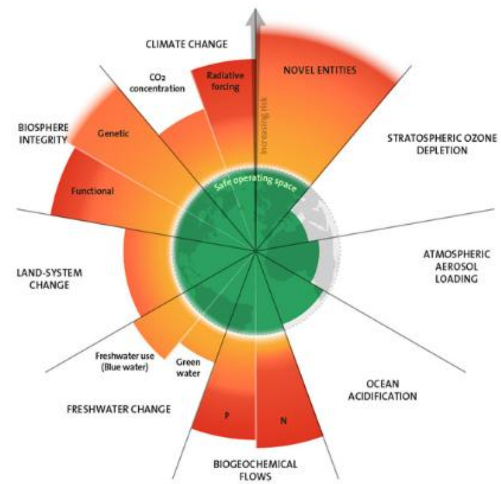
7 boundaries assessed, 3 crossed

2015



7 boundaries assessed, 4 crossed

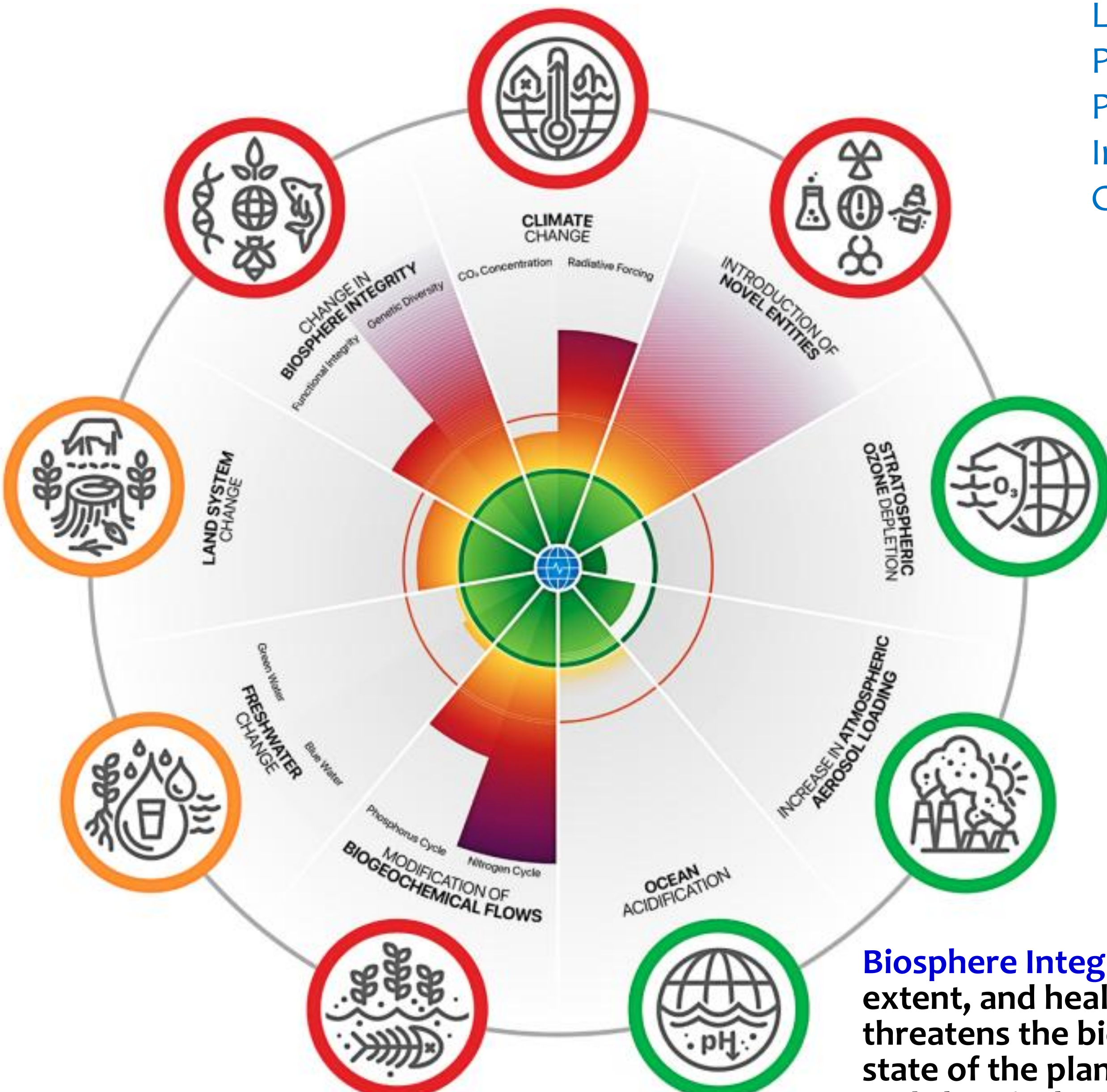
2023



9 boundaries assessed, 6 crossed

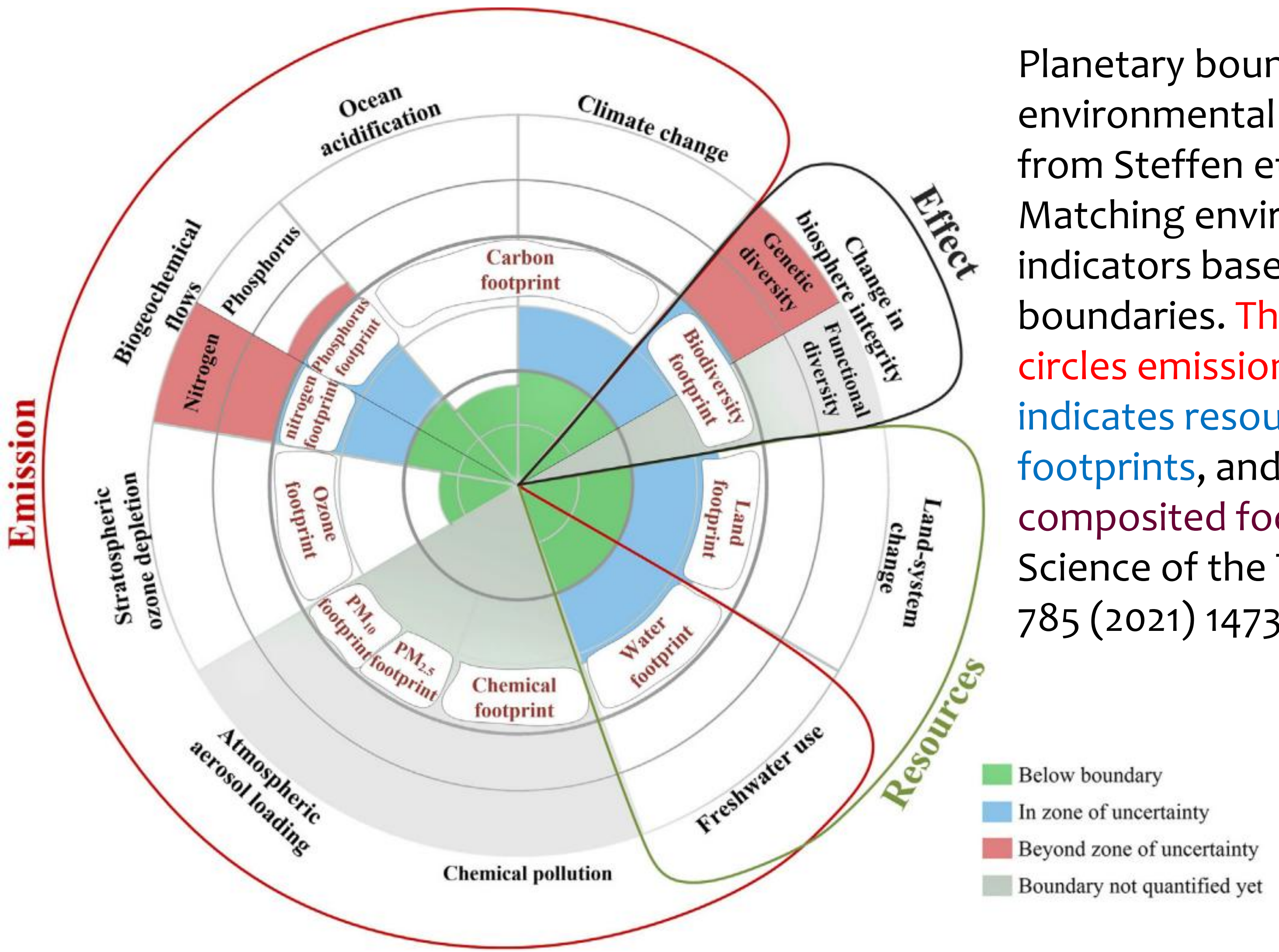
https://www.stockholmresilience.org/research/planetary-boundaries.html

L. Caesar*, B. Sakschewski*, et. al., Planetary Health Check Report 2024. Potsdam Institute for Climate Impact Research, Potsdam, Germany.



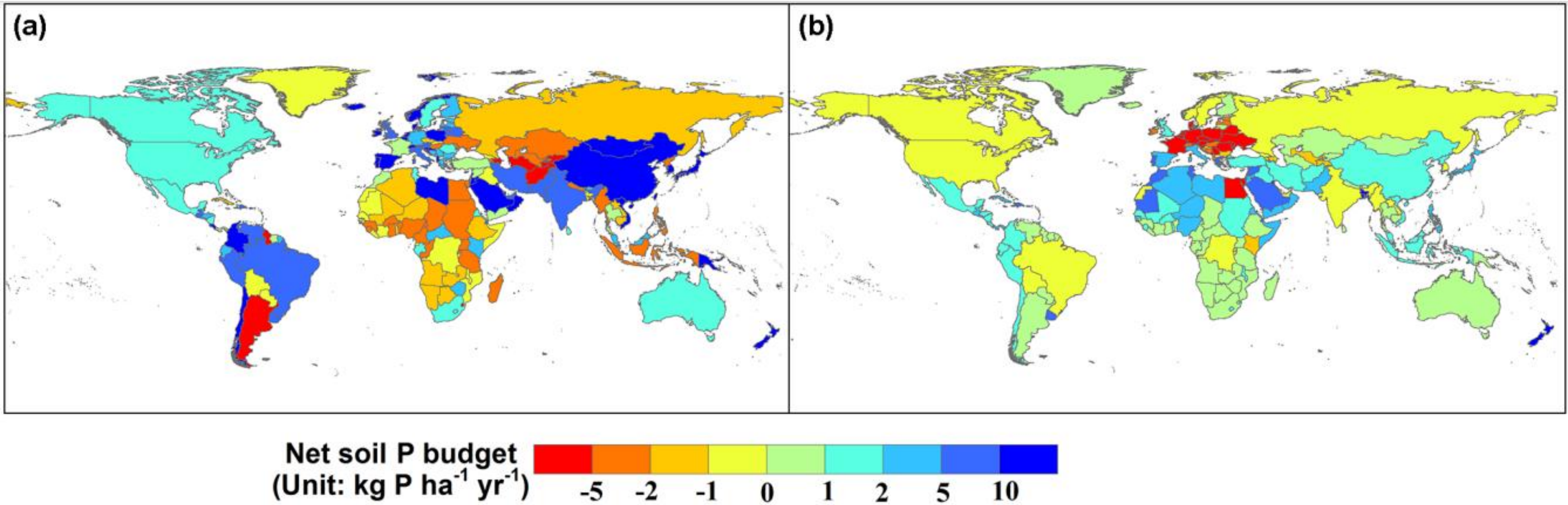
Biosphere Integrity: The decline in the diversity, extent, and health of living organisms and ecosystems threatens the biosphere's ability to co-regulate the state of the planet by impacting the energy balance and chemical cycles on Earth.

Biogeochemical flow: The disruption of global nutrient cycles of nitrogen and phosphorus negatively affects soil health, water quality, and biodiversity and triggers dead zones in freshwater and marine systems.



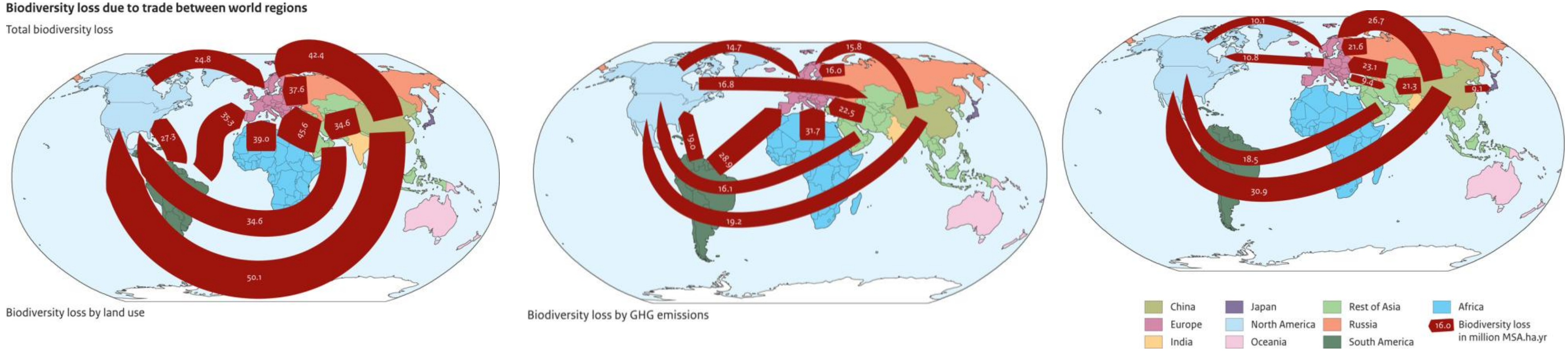
Planetary boundaries and environmental footprints (updated from Steffen et al. (2015b)): Matching environmental footprint indicators based on planetary boundaries. The outer red line circles emission footprints, green indicates resource consumption footprints, and black indicates composited footprints.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

Earth Syst. Sci. Data, 10, 1–18, 2018
https://doi.org/10.5194/essd-10-1-2018



Map of global net soil P budgets (positive values, increase; negative values, decrease) for (a) cropland and (b) pasture

Foodstuff	Quantity	Water consumption, litres
Source: IME		
Chocolate	1 kg	17,196
Beef	1 kg	15,415
Sheep Meat	1 kg	10,412



Trade in biodiversity loss among 10 world regions and countries, and for the primary pressure categories (total, land use, and GHG emissions). Each part shows the ten trade flows causing the highest losses. The arrows start in the regions where the pressures take place and end in the consuming regions. Losses are measured in million MSA-loss·ha·yr. [Environ. Sci. Technol. 2017, 51, 6, 3298–3306]

Systematic quantification of these losses in relation to land use and greenhouse gas (GHG) emissions associated with the production and consumption of (inter) nationally traded goods and services by presenting consumption-based biodiversity losses, in short, biodiversity footprint.

The biodiversity footprint per dollar consumed is lower for wealthier countries.