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Harnessing complementary curricular preparedness
via sustainable management in response to civil and military pollution
on the coastline, tributaries and lagoons in Black Sea's North, West, South zone

INTELLIGENT **GEOPOLYMER**-BASED MATERIALS FOR MARINE POLLUTION MITIGATION AND ENVIRONMENTAL PROTECTION



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COURSE COORDINATOR & LECTURER

Dumitru-Doru BURDUHOS-NERGIŞ, Ph.D. Eng.

Senior Lecturer



EDUCATION

- Ph.D. in Materials Engineering – Gheorghe Asachi Technical University of Iasi, Romania
- Postdoctoral studies in Materials Engineering



EXPERTISE & RESEARCH AREAS

- Materials Science: geopolymers, composites, innovative coatings
- Environmental Science: soil decontamination, recycling, waste valorization
- Intellectual Property: patent writing & design, promotion, development



SCIENTIFIC ACHIEVEMENTS

- >60 scientific articles (51 indexed in WoS)
- Citations: WoS >1150 | Scopus >1450 | Google Scholar >1950
- H-index: WoS 18 | Scopus 21 | Google Scholar 23



PROFESSIONAL ACTIVITIES

- Editor: *Materials* (MDPI), Taylor and Francis
- Reviewer: >400 verified reviews
- Organizer: EUROINVENT & ICIR EUROINVENT (2018–2026)
- International collaborations with >20 institutions worldwide



>1150 / >1450 / >1950

Citations (WoS / Scopus / Google Scholar)



18 / 21 / 23

H-index (WoS / Scopus / Google Scholar)



6 / 18 / 3 / 2

International books / book chapters /
national books / books as editor



10 (1 as Director/Responsible)

Research projects



1 / 5

Patent granted / patent applications (RO)



**Extensive national & international
cooperation in research and projects**



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COURSE AIM & LEARNING OBJECTIVES

This course explores **intelligent geopolymer-based materials** as innovative, sustainable and low-carbon solutions for marine pollution mitigation, wastewater treatment and environmental protection. Learners will gain knowledge on their design, mechanisms, applications and integration in a circular economy.



OBJECTIVE 1

Define geopolymer-based materials and explain their relevance for environmental protection



OBJECTIVE 2

Describe the main types of marine pollutants targetable by geopolymer systems



OBJECTIVE 3

Understand adsorption, ion-exchange, encapsulation and immobilization mechanisms



OBJECTIVE 4

Explain the concept of "intelligent" or functionalized geopolymer materials



OBJECTIVE 5

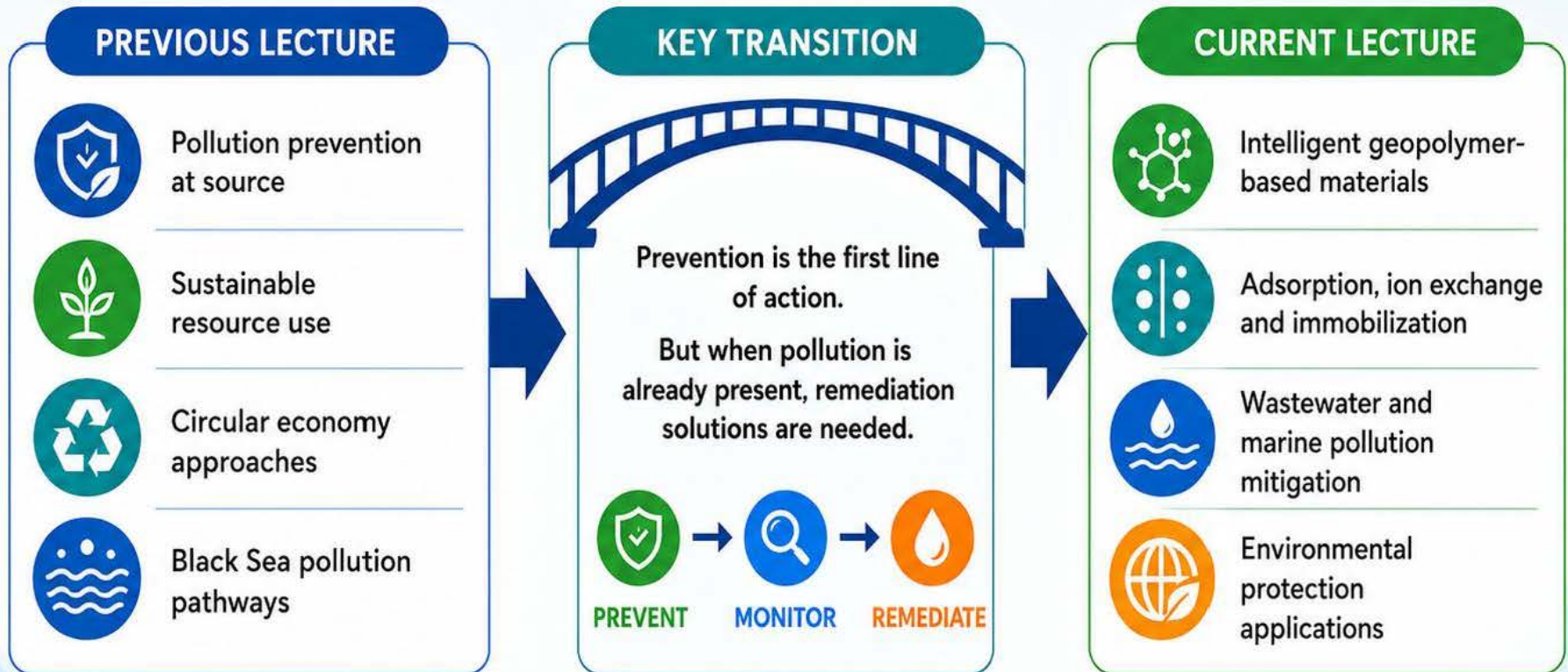
Identify applications in wastewater treatment, coastal remediation and circular economy



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LINK WITH THE PREVIOUS LECTURE

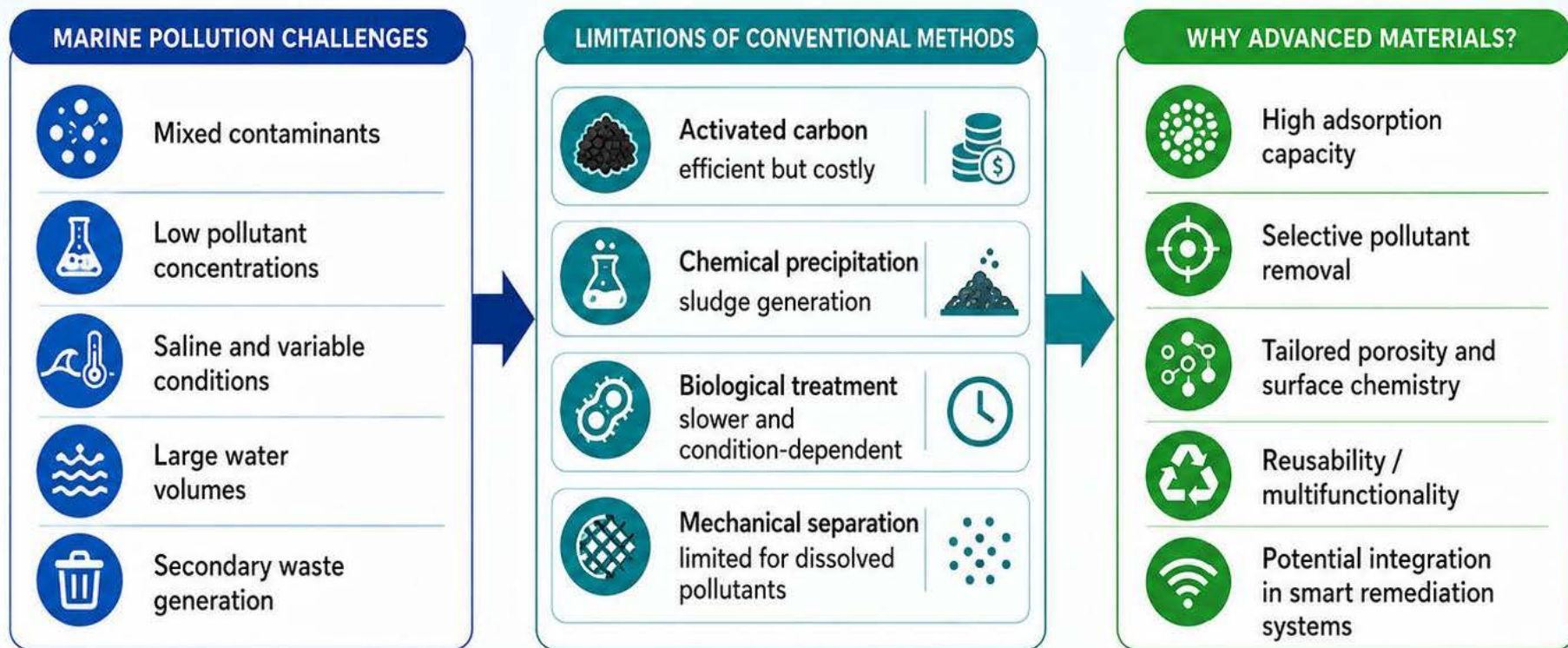
From prevention to remediation materials



This lecture complements the previous course by *moving from* broad prevention strategies to advanced material-based mitigation solutions.

WHY ADVANCED MATERIALS ARE NEEDED IN MARINE POLLUTION MITIGATION

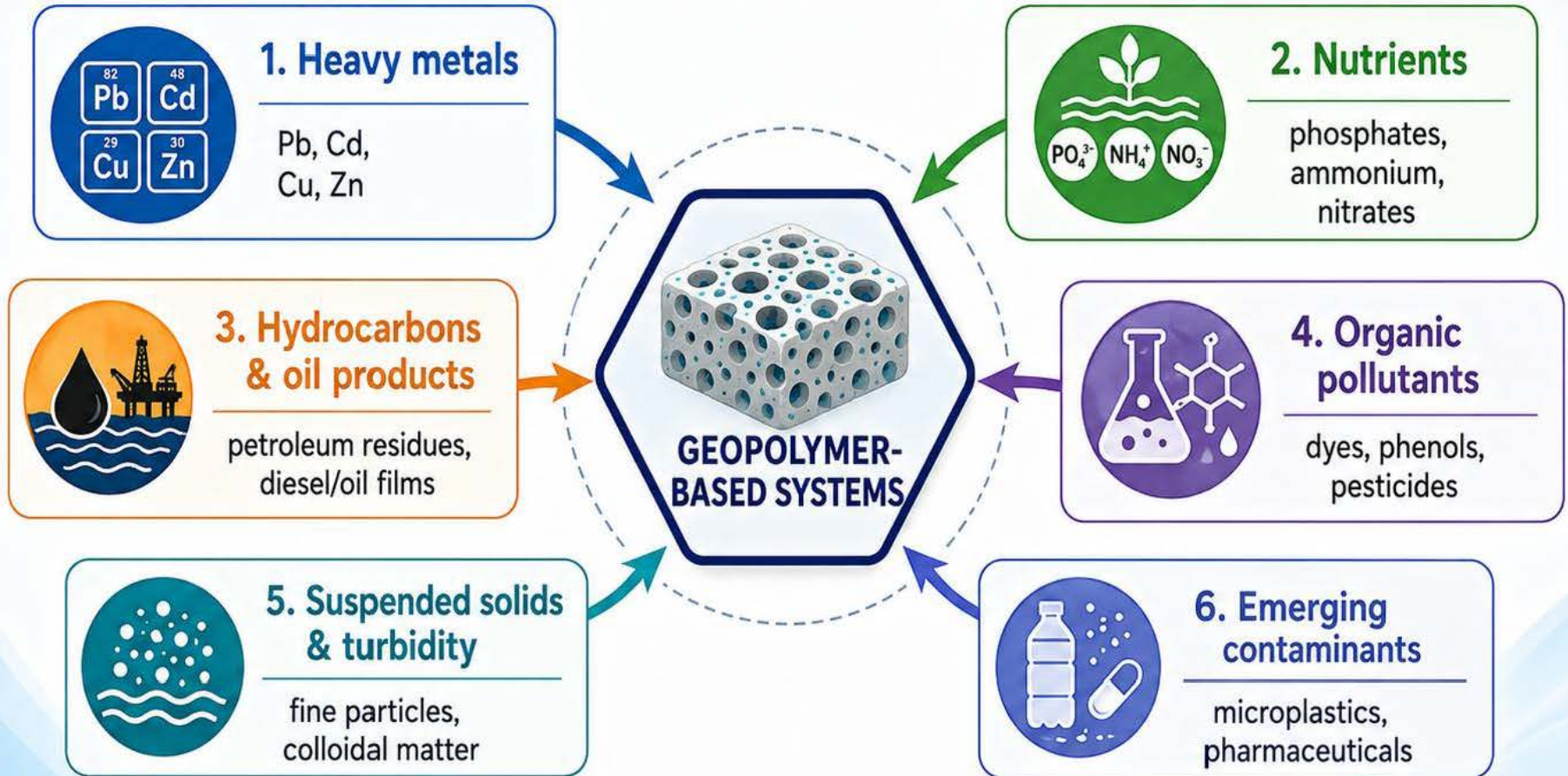
Addressing complex pollutants with high-performance functional solutions



Advanced materials can improve efficiency, selectivity and sustainability in marine pollution mitigation.

MARINE POLLUTANTS TARGETED BY GEOPOLYMER SYSTEMS

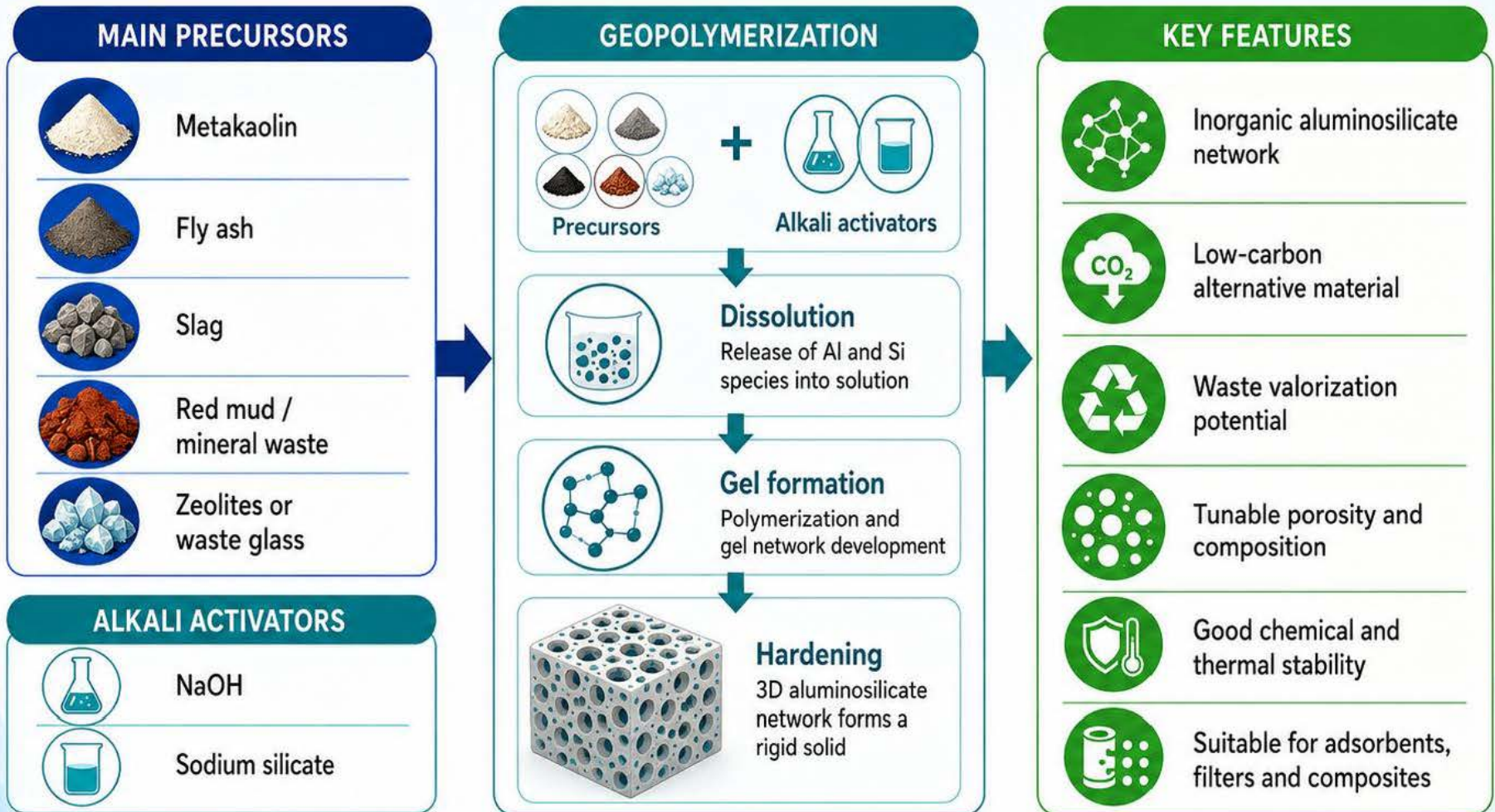
From dissolved ions to complex organic and particulate contaminants



Geopolymer materials can address multiple pollutant classes through adsorption, ion exchange and immobilization.

WHAT ARE GEOPOLYMER-BASED MATERIALS?

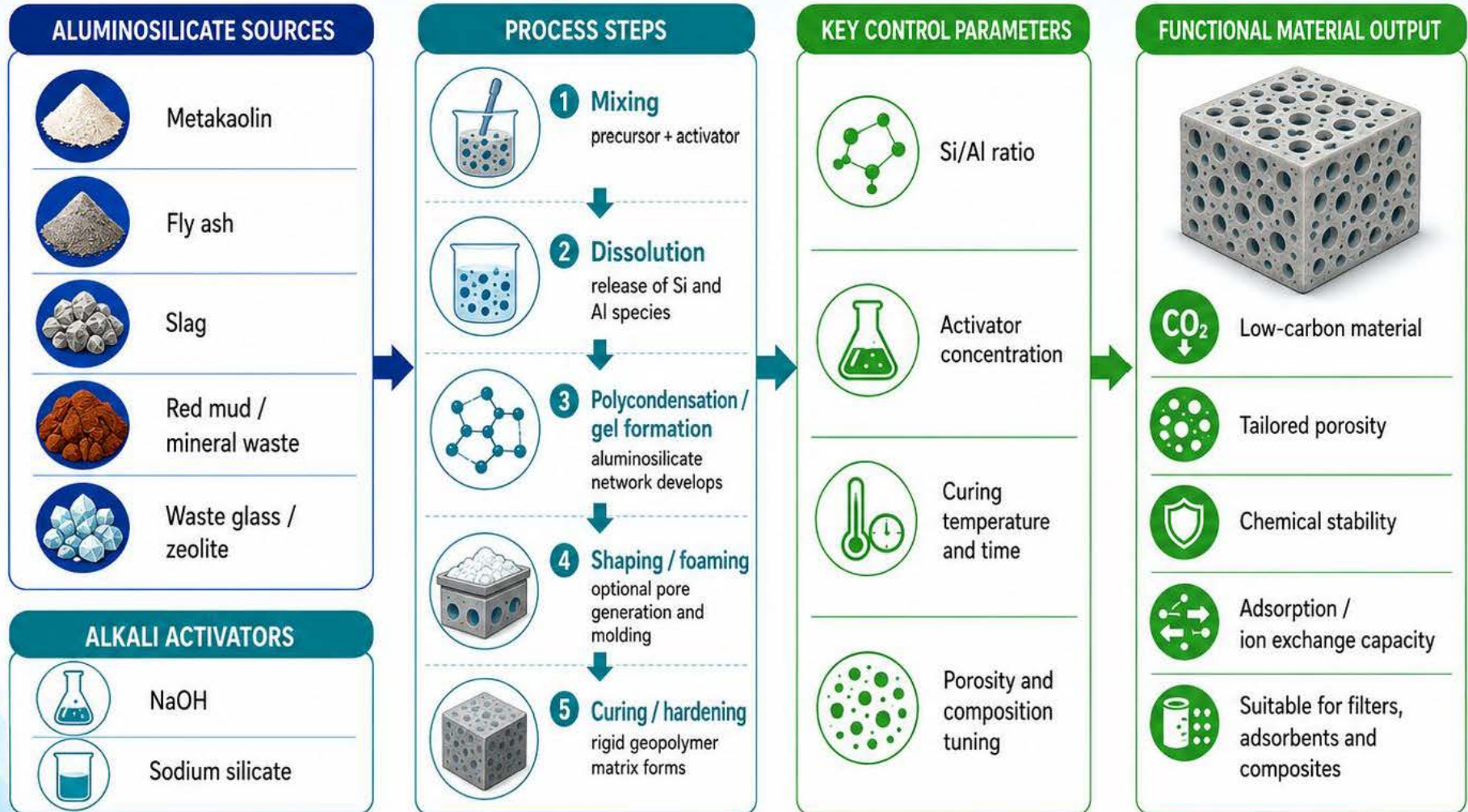
Low-carbon alkali-activated aluminosilicate materials for functional environmental applications



Geopolymer-based materials are alkali-activated inorganic solids that can be tailored into sustainable filters, adsorbents and remediation systems.

GEOPOLYMERIZATION TECHNOLOGY

From aluminosilicate waste to functional material



Geopolymerization transforms mineral precursors and waste streams into tunable functional materials for environmental applications.

WHY GEOPOLYMERS ARE SUITABLE FOR ENVIRONMENTAL PROTECTION

Combining sustainability, functional performance and adaptability for remediation applications

SUSTAINABILITY BENEFITS



Low-carbon alternative



Waste valorization potential



Reduced raw material demand



Long service life



Possibility of reuse or regeneration

FUNCTIONAL ADVANTAGES



Tunable porosity



Ion exchange capacity



Adsorption and immobilization



Good chemical stability



Multi-pollutant removal potential

PRACTICAL RELEVANCE



Suitable for filters and adsorbents



Can be used in composites and barriers



Adaptable to marine and wastewater systems



Compatible with circular economy strategies



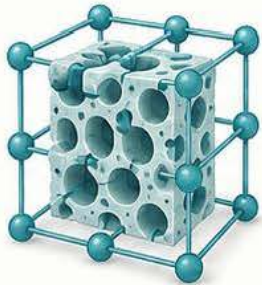
Potential integration in smart remediation systems



Geopolymers are promising environmental materials because they combine sustainability, performance and design flexibility in a single remediation platform.

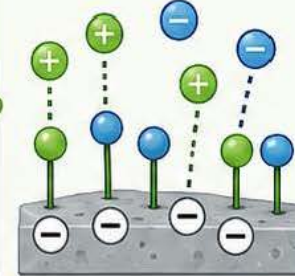
WHAT MAKES A GEOPOLYMER "INTELLIGENT"?

Functional design, adaptive chemistry and multifunctionality for advanced remediation



1. TAILORED STRUCTURE

- tunable porosity
- controlled pore size
- adjustable composition
- shaped as filters, pellets or monoliths

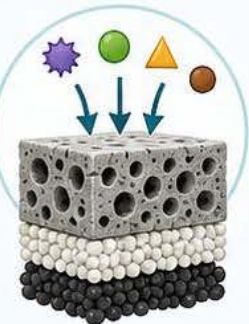


2. ACTIVE SURFACE CHEMISTRY

- adsorption sites
- ion-exchange capacity
- surface functionalization
- selective interaction with pollutants

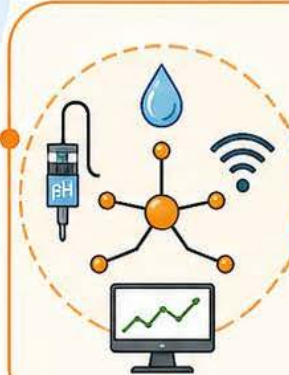


**INTELLIGENT
GEOPOLYMER**



3. MULTIFUNCTIONAL BEHAVIOUR

- captures several pollutant types
- combines filtration and immobilization
- can host zeolite or carbon additives
- suitable for hybrid systems



4. SMART APPLICATION POTENTIAL

- adaptable to different water matrices
- reusable or regenerable in some systems
- compatible with monitoring strategies
- useful in advanced remediation platforms



A geopolymer is considered 'intelligent' when its structure and chemistry are deliberately engineered to deliver selective, adaptable and multifunctional pollutant removal.

TAILORED POROSITY: FROM MACROPORES TO NANOPORES

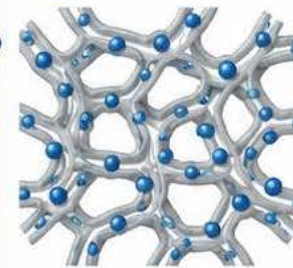
Hierarchical pore architecture controls transport, adsorption and pollutant capture

1 MACROPORES (>50 μm)



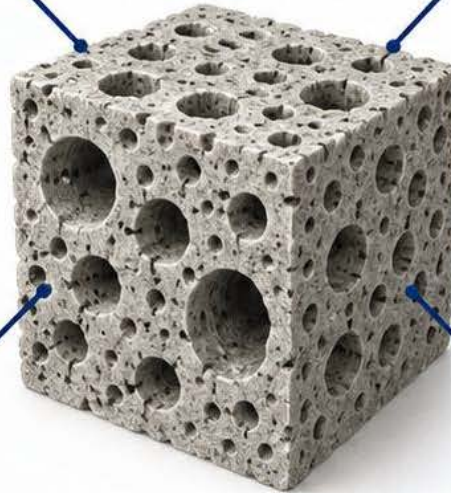
- fluid flow and low pressure drop
- transport channels through the filter
- useful for monoliths and foamed structures

2 MESOPORES (2–50 nm)

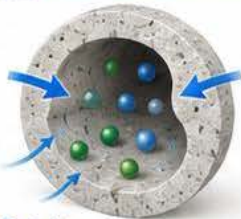


- increased accessible surface area
- improved diffusion to active sites
- supports adsorption kinetics

POROUS GEOPOLYMER



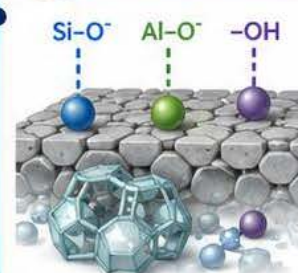
3 MICROPORES (<2 nm)



● Cation
● Molecule

- strong adsorption potential
- confinement of small ions and molecules
- important for selective capture

4 NANOSCALE SURFACE FEATURES



- active sites and surface charge
- ion exchange and interfacial interactions
- can be enhanced by zeolite or functional additives

Transport



Diffusion



Adsorption



Immobilization



Hierarchical porosity enables geopolymer materials to combine permeability, surface area and selective pollutant retention in a single remediation platform.

ACTIVE SURFACE CHEMISTRY AND ION-EXCHANGE CAPACITY

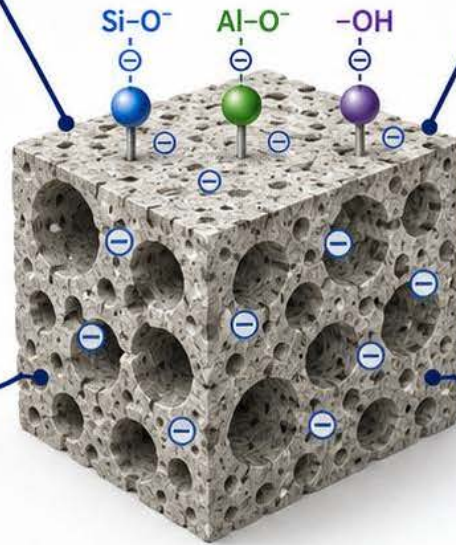
Surface charge, functional groups and exchangeable sites govern selective pollutant capture

1. ACTIVE SURFACE SITES



- Si-O^- and Al-O^- groups
- surface hydroxyls ($-\text{OH}$)
- charged adsorption sites
- interaction with dissolved species

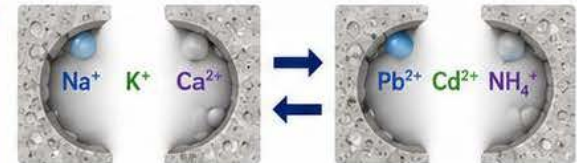
GEOPOLYMER SURFACE



2. ION-EXCHANGE MECHANISM

BEFORE (in material)

AFTER (in water)



- exchangeable cations in pores
- replacement by metal ions or ammonium
- reversible or semi-permanent retention

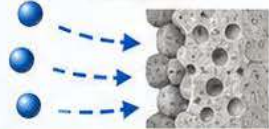
3. TARGET POLLUTANTS

- Pb^{2+} heavy metals: Pb^{2+} , Cd^{2+} , Cu^{2+} , Zn^{2+}
- NH_4^+ ammonium: NH_4^+
- PO_4^{3-} phosphate-related species / nutrient interactions
- organic molecules through surface interactions

4. FACTORS AFFECTING PERFORMANCE

- pH and ionic strength
- Si/Al ratio
- porosity and diffusion access
- presence of zeolite or additives
- competing ions in saline water

Diffusion



Surface interaction



Ion exchange / adsorption



Immobilization

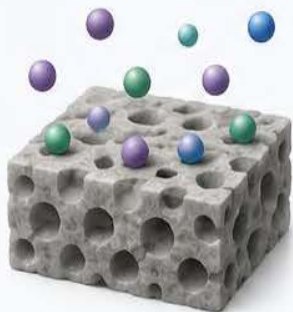


The environmental performance of geopolymer materials depends strongly on their active surface chemistry and their ability to exchange and immobilize pollutant ions.

13 Main removal mechanisms

Geopolymers remove pollutants through multiple complementary mechanisms.

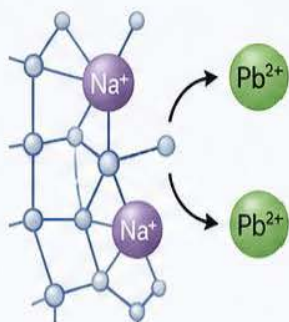
1. Adsorption



Pollutants adhere to the surface via physical and chemical interactions.

- Electrostatic attraction
- Hydrogen bonding
- Van der Waals forces
- Surface complexation

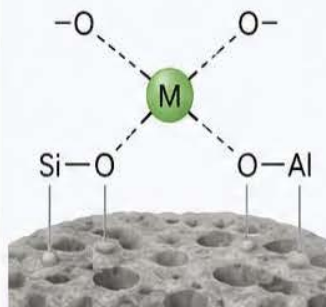
2. Ion exchange



Exchangeable cations in the geopolymer structure are replaced by pollutant ions.

- High affinity for heavy metals (Pb^{2+} , Cd^{2+} , Cu^{2+} ...)
- Selective and reversible
- pH-dependent

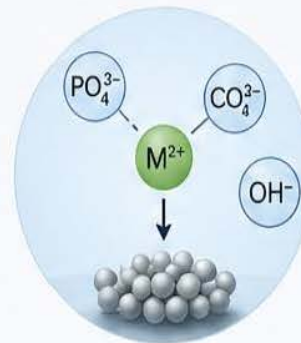
3. Complexation & chelation



Pollutants form inner-sphere complexes with surface functional groups.

- Strong, specific binding
- Involves $-\text{OH}$, $-\text{COO}-$, $-\text{Si-OH}$, $-\text{Al-OH}$ groups
- Often leads to immobilization

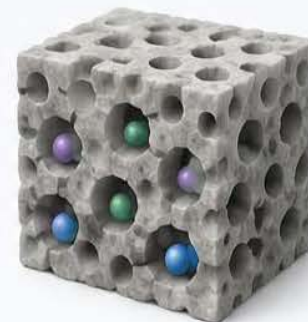
4. Precipitation



Pollutants are converted into insoluble compounds on the geopolymer surface or in pores.

- Hydroxides (e.g., $\text{M}(\text{OH})_2$)
- Carbonates (e.g., MCO_3)
- Phosphates (e.g., $\text{M}_3(\text{PO}_4)_2$)
- Reduces mobility and toxicity

5. Physical entrapment & filtration



Pollutants are trapped within the pore structure or on the internal surfaces.

- Size exclusion
- Tortuosity and pore blocking
- Enhances retention and reduces desorption

→ Synergy of mechanisms

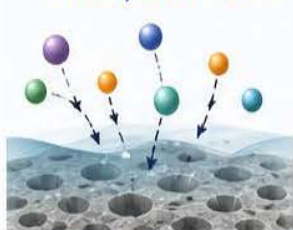
The combination of these mechanisms gives geopolymers high efficiency, selectivity, and stability in diverse environmental conditions.



Geopolymers efficiently capture heavy metal ions from water and immobilize them within a chemically stable matrix, reducing mobility, bioavailability and toxicity.

From adsorption at the surface to immobilization in the matrix

1. Transport to surface



Metal ions (e.g., Pb^{2+} , Cd^{2+} , Cu^{2+} , Ni^{2+} , Cr^{6+}) diffuse through the solution to the geopolymer surface.

2. Adsorption & ion exchange



Ions bind to active sites via adsorption and exchange with charge-balancing cations (Na^+ , K^+ , Ca^{2+}).

3. Immobilization in the matrix



Metals are incorporated into the geopolymer network or precipitated as insoluble phases.



Benefits of immobilization

- Strong and stable binding reduces leaching
- Lower bioavailability and ecological risk
- High durability in various environmental conditions (pH, redox, temperature)
- Effective for a wide range of heavy metals
- Enables long-term containment and safer waste valorization



Key factors influencing performance



Porosity and surface area



Si/Al ratio and geopolymer composition



Type and density of functional groups

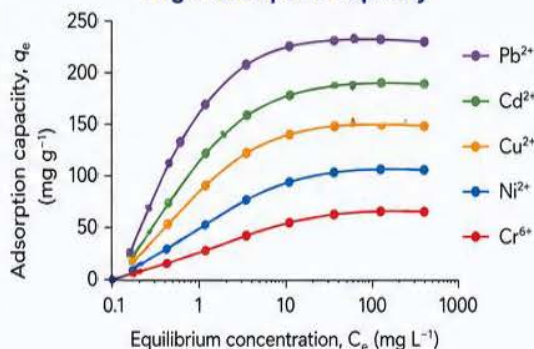


pH, ionic strength, competing ions



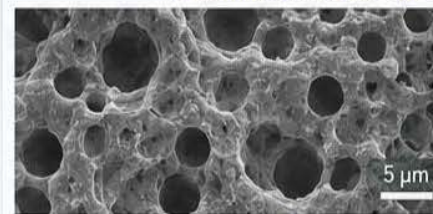
Curing conditions and degree of geopolymerization

High adsorption capacity

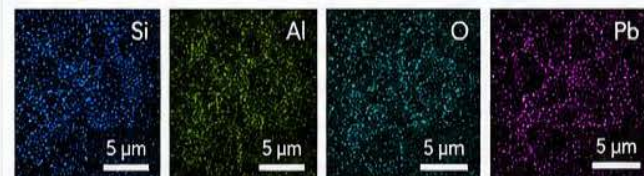


Geopolymers show high capacity for various heavy metals.

Immobilization evidence



SEM-EDS mapping shows uniform distribution of Pb within the geopolymer matrix, indicating strong immobilization.



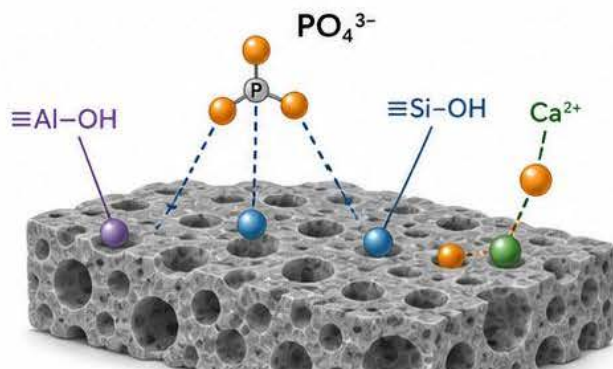
Outcome: safe and durable immobilization

Heavy metals are captured and locked within the geopolymer structure, ensuring long-term environmental protection and supporting the circular use of aluminosilicate wastes.



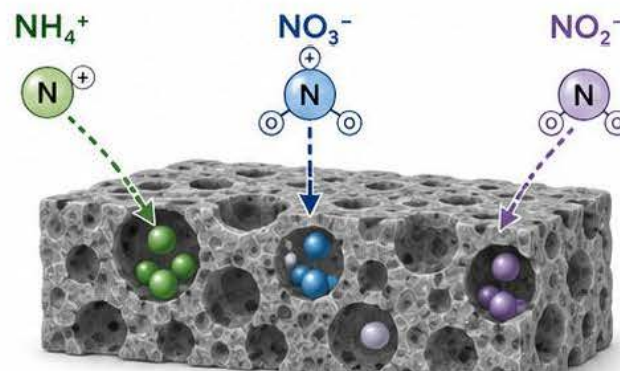
Geopolymer-based materials can remove nutrient species through surface interactions, ion exchange and precipitation, helping to reduce eutrophication risk.

Phosphate removal (PO_4^{3-})



- adsorption on surface hydroxyl groups
- complexation with Al-O and Si-O sites
- precipitation with Ca-containing phases or metal cations
- useful for lowering eutrophication pressure

Nitrogen compounds removal



- ammonium removal mainly through ion exchange
- nitrate and nitrite reduction is more limited and system-dependent
- surface interactions and pore diffusion influence retention
- zeolite-containing systems can improve ammonium capture



Key factors



- geopolymer composition and Si/Al ratio



- pore structure and accessible surface area



- pH, salinity and competing ions



- presence of zeolite or added Ca phases



Environmental relevance



- reduced nutrient loading



- lower algal bloom risk



- improved water quality in coastal and transitional waters



- suitable for filtration-based treatment concepts



Project-oriented message



In Black Sea water filtration concepts, geopolymer and geopolymer-zeolite systems showed potential for reducing phosphate and nitrogen-related species.



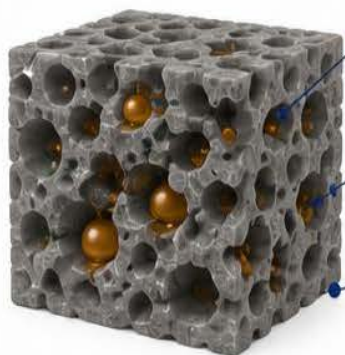
For nutrient removal, geopolymer performance depends strongly on composition, active surface chemistry and the design of the filtration system.



16 Hydrocarbon and oil-product retention

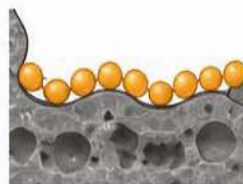
Geopolymers effectively retain hydrocarbons and oil products through physical entrapment, adsorption and surface interactions, reducing their mobility and environmental impact.

1. How geopolymers retain hydrocarbons



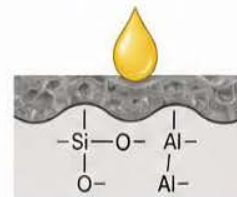
- **Physical entrapment**
Oil is trapped within the interconnected macropores and mesopores.
- **Adsorption on surface**
Hydrophobic interactions and van der Waals forces promote oil adsorption on pore walls.
- **Surface chemistry interactions**
Si-O-Si, Al-O-Si and other functional groups interact with polar fractions of oil, enhancing retention.

2. Mechanisms involved



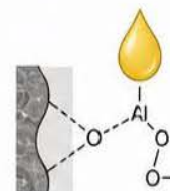
Pore filling

Oil is held inside pores by capillary forces and size exclusion.



Adsorption

Nonpolar interactions and π - π stacking with aromatic compounds in oil.



Chemical interactions

Polar components in oil interact with active sites (e.g., -OH, -COO-, -Si-O-).

3. Key advantages

- ✓ **High oil uptake capacity**
Large pore volume and surface area enable high retention.
- ✓ **Strong immobilization**
Oil remains trapped even under flow or agitation.
- ✓ **Chemical and thermal stability**
Maintains performance in harsh environments (salinity, pH, temperature).
- ✓ **Reusability potential**
Oil can be removed by mild washing or solvent extraction for material reuse.
- ✓ **Environmentally friendly**
Made from industrial by-products; low carbon footprint.

4. Applications



Oil spill clean-up

Absorbs and retains oil from water surfaces and contaminated sites.



Wastewater treatment

Removes dispersed and dissolved oil from industrial effluents.



Produced water treatment

Reduces oil content in water from oil & gas operations.



Soil remediation

Immobilizes hydrocarbons in contaminated soils and sediments.

5. Environmental impact



Reduces the spread and toxicity of oil pollutants in water and soil.



Protects aquatic ecosystems and biodiversity.



Supports sustainable management of oil-contaminated environments.



Key message

Geopolymers combine tailored porosity and active surface chemistry to efficiently retain hydrocarbons and oil products, offering a durable, sustainable and effective solution for water and soil decontamination.

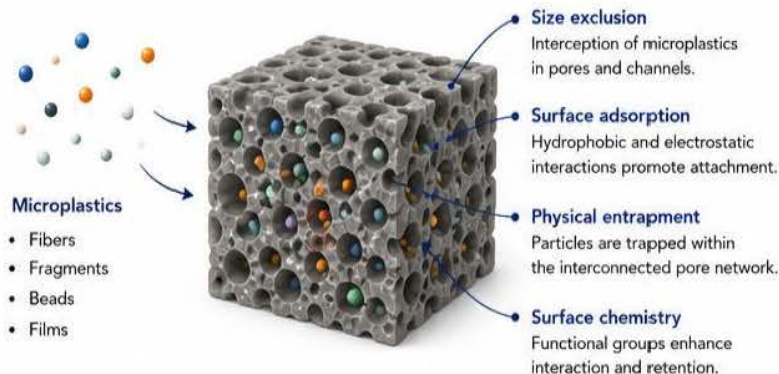
Typical oil uptake capacity*

5 – 30 g oil / g geopolymer

(*depending on composition and conditions)

Geopolymers offer a versatile platform for capturing microplastics and a wide range of emerging contaminants from water and wastewater, contributing to advanced and sustainable treatment solutions.

1. Microplastics removal: how geopolymers work



Key factors influencing removal



2. Emerging contaminants: potential removal

Geopolymers can adsorb and/or immobilize a broad spectrum of emerging pollutants through diverse interaction mechanisms.



Main interaction mechanisms



3. Advantages of geopolymers for advanced contaminants

- ✓ High surface area and tailored porosity
- ✓ Diverse and tunable surface chemistry
- ✓ High stability in a wide range of pH and temperatures
- ✓ Capability to target multiple contaminants simultaneously
- ✓ Low cost, sustainable, and made from industrial by-products
- ✓ Potential for regeneration and reuse

4. Potential applications

- Drinking water treatment**
Removal of microplastics and trace contaminants.
- Wastewater and effluent polishing**
Elimination of emerging pollutants from municipal and industrial discharges.
- Advanced treatment systems**
Integration in adsorption filters, membrane pre-treatment, constructed wetlands, and hybrid systems.
- Environmental remediation**
Removal from contaminated soils, sediments, and surface waters.

5. Environmental and societal benefits

- Protects aquatic ecosystems and biodiversity
- Reduces exposure to harmful emerging pollutants
- Supports circular economy and resource recovery
- Helps advance sustainable development goals (SDGs 3, 6, 12, 14, 15)



Key message

Thanks to their smart porosity and active surface chemistry, geopolymers are promising materials for next-generation removal of microplastics and a broad range of emerging contaminants.

*PFAS – Per- and polyfluoroalkyl substances

18 Geopolymer–zeolite composites: why functional phases matter

Integrating zeolites into geopolymer matrices creates synergistic materials in which functional phases provide specific active sites, ion-exchange capacity and molecular sieving, enhancing overall performance.

1. What are geopolymer–zeolite composites?



2. Why functional phases matter



Enhanced adsorption

Zeolites provide additional active sites and high surface area for adsorbing ions and organic molecules.



Ion-exchange capacity

Exchangeable cations in zeolites (Na^+ , K^+ , Ca^{2+}) improve removal of heavy metals and ammonium.



Molecular sieving & selectivity

Ordered micropores allow selective uptake based on size and shape, enhancing removal of target pollutants.



Improved stability & durability

Zeolites enhance thermal, chemical and mechanical stability of geopolymer matrices.



Synergistic performance

Combination of physisorption, chemisorption, ion exchange and precipitation mechanisms.

3. Key functional contributions of zeolites

Zeolite property	Functional role	Benefits in composite
 High surface area & microporosity	Provides abundant adsorption sites	Higher removal capacity for heavy metals, organics, dyes, nutrients and emerging contaminants
 Cation exchange (CEC)	Exchanges framework cations with pollutants	Effective removal of NH_4^+ , Pb^{2+} , Cd^{2+} , Cu^{2+} , and other cations
 Uniform pore size and structure	Size and shape selective adsorption	Selective removal of specific molecules; reduced competition from co-existing species
 Acidic sites (Brønsted/Lewis)	Catalytic and interaction sites for organics	Improved degradation or retention of organic pollutants and micropollutants
 Chemical compatibility	Good interfacial bonding with geopolymer	Stable integration, reduced leaching and long-term performance

4. Examples of enhanced performance

- ✓ Greater uptake of heavy metals due to combined adsorption + ion exchange.
- ✓ Enhanced ammonium removal from wastewater.
- ✓ Improved phosphate removal through surface complexation and exchange.
- ✓ Better retention of organic pollutants and pharmaceuticals.
- ✓ Higher durability and reusability of adsorbents.

Performance depends on:

- Zeolite type (e.g., clinoptilolite, zeolite A, X)
- Zeolite content and distribution
- Interfacial bonding and composite synthesis
- Pore structure and surface chemistry

5. Applications



Water and wastewater treatment
(Removal of metals, nutrients, organics, dyes, pharmaceuticals, PFAS*)



Soil and groundwater remediation
(Stabilization/immobilization of contaminants)



Industrial effluents and process water
(Heavy metals, ammonium, organics)



Sustainable materials development
(Value-added use of industrial by-products with tailored functionality)



Key message

Functional phases like zeolites turn geopolymers into high-performance adsorbents and remediation materials by providing specific active sites, ion-exchange capacity and selectivity, leading to superior and durable solutions for diverse environmental challenges.

*PFAS – Per- and polyfluoroalkyl substances

Metakaolin-based geopolymer filters were designed to remove pollutants and improve water quality in the Black Sea, addressing specific challenges such as heavy metals, nutrients, and organic micropollutants.

1. Materials and synthesis



- Geopolymerization of metakaolin at ambient or moderate temperature
- Shaping into porous monolithic filters
- High mechanical stability and chemical resistance in marine environment

2. Black Sea water: key challenges



- Heavy metals** (Pb²⁺, Cd²⁺, Cu²⁺, Zn²⁺) from rivers and anthropogenic activities
- Nutrients** (phosphates, nitrates, ammonium) causing eutrophication
- Organic micropollutants** (pharmaceuticals, phenols, pesticides) from urban and industrial sources
- Microplastics** accumulating in marine environment

3. Filter performance

Pollutant group	Removal efficiency (%) *	Main removal mechanisms
Heavy metals	90 – 98	• Ion exchange • Surface complexation • Precipitation within pores
Phosphates (PO ₄ ³⁻)	85 – 95	• Ligand exchange with –OH groups • Complexation with Al–O sites • Precipitation with Ca²⁺/metal ions
Nitrogen compounds (NO ₃ ⁻ , NH ₄ ⁺)	70 – 90	• Ion exchange (NH₄⁺) • Adsorption of NO₃⁻ • Surface interactions
Organic micropollutants (phenols, PPCPs ^{**})	70 – 95	• Hydrophobic adsorption • π–π interactions • Pore filling and trapping
Microplastics	> 80	• Physical straining • Surface attachment • Pore blocking and retention

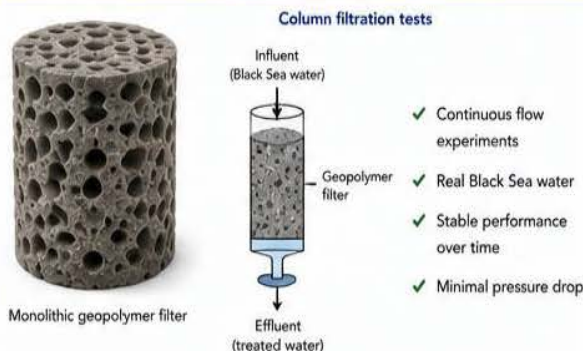
* Typical range reported for laboratory/column tests under optimized conditions.

** PPCPs – Pharmaceuticals and Personal Care Products.

4. Why metakaolin-based geopolymers?

- Sustainable raw material**
Metakaolin is abundant, low-cost and industrial by-product.
- High chemical and mechanical stability**
Resistant to saline, alkaline and variable conditions of the Black Sea.
- Tailorable porosity and surface chemistry**
Enables efficient removal of diverse pollutants.
- Long-term durability and reusability**
Filters can be regenerated and reused multiple times.
- Eco-friendly and low carbon footprint**
Lower environmental impact compared to conventional materials.

5. Prototype filter and testing



6. Environmental relevance

- Improves water quality in coastal areas
- Reduces nutrient loading and eutrophication
- Protects marine ecosystems and biodiversity
- Supports sustainable management of Black Sea resources
- Contributes to circular economy and blue growth



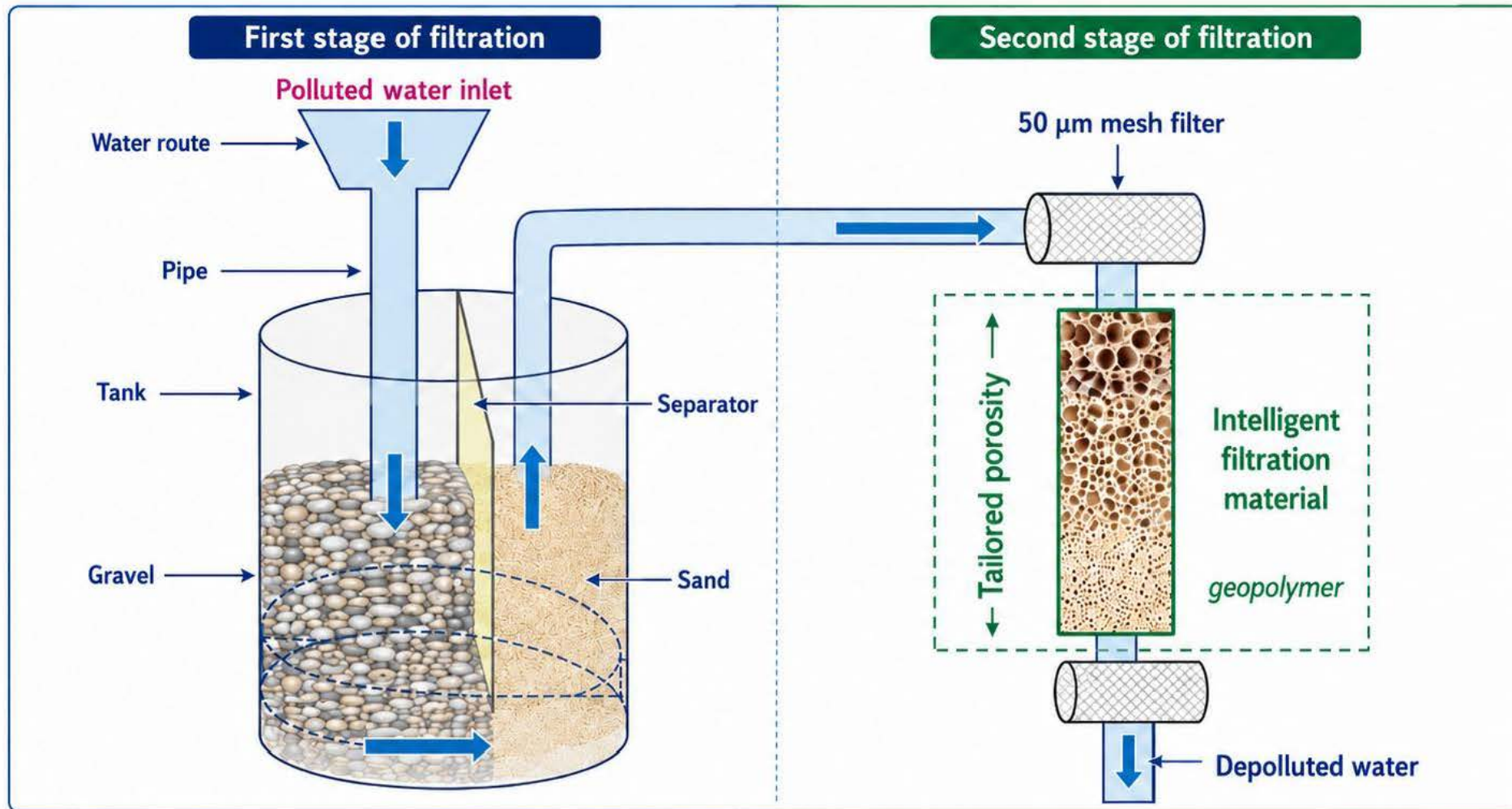
Key message

Metakaolin-based geopolymer filters are effective, durable and sustainable solutions for treating Black Sea water, removing heavy metals, nutrients, organic micropollutants and microplastics, and contributing to the protection of marine environment and human health.

Developed and tested for Black Sea conditions
High performance – Sustainable future

20 Experimental filtration system and operating principle

Schematic representation of the two-stage experimental system used for Black Sea water treatment.



Stage 1 function

- Coarse filtration and particle separation using gravel and sand.



Stage 2 function

- Fine filtration using a 50 μm mesh and geopolymer-based intelligent filtration material with tailored porosity.

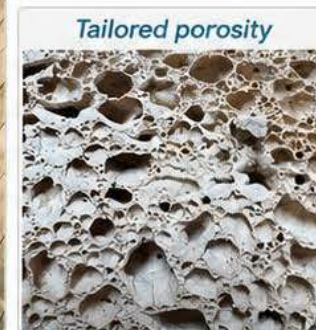
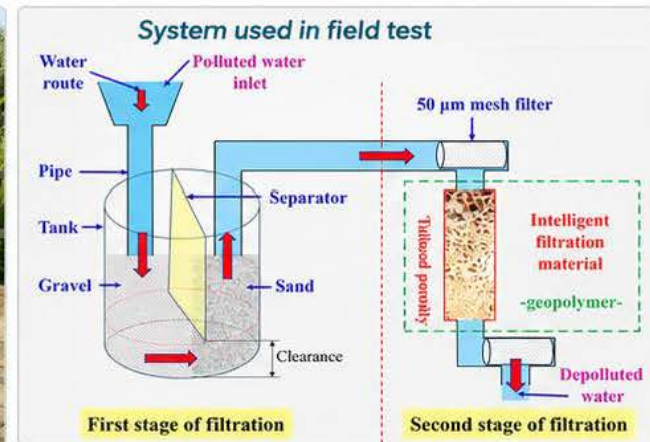


Operating principle

- Sequential treatment from polluted water inlet to depolluted water through two complementary stages.

20 In situ testing of the experimental filtration system

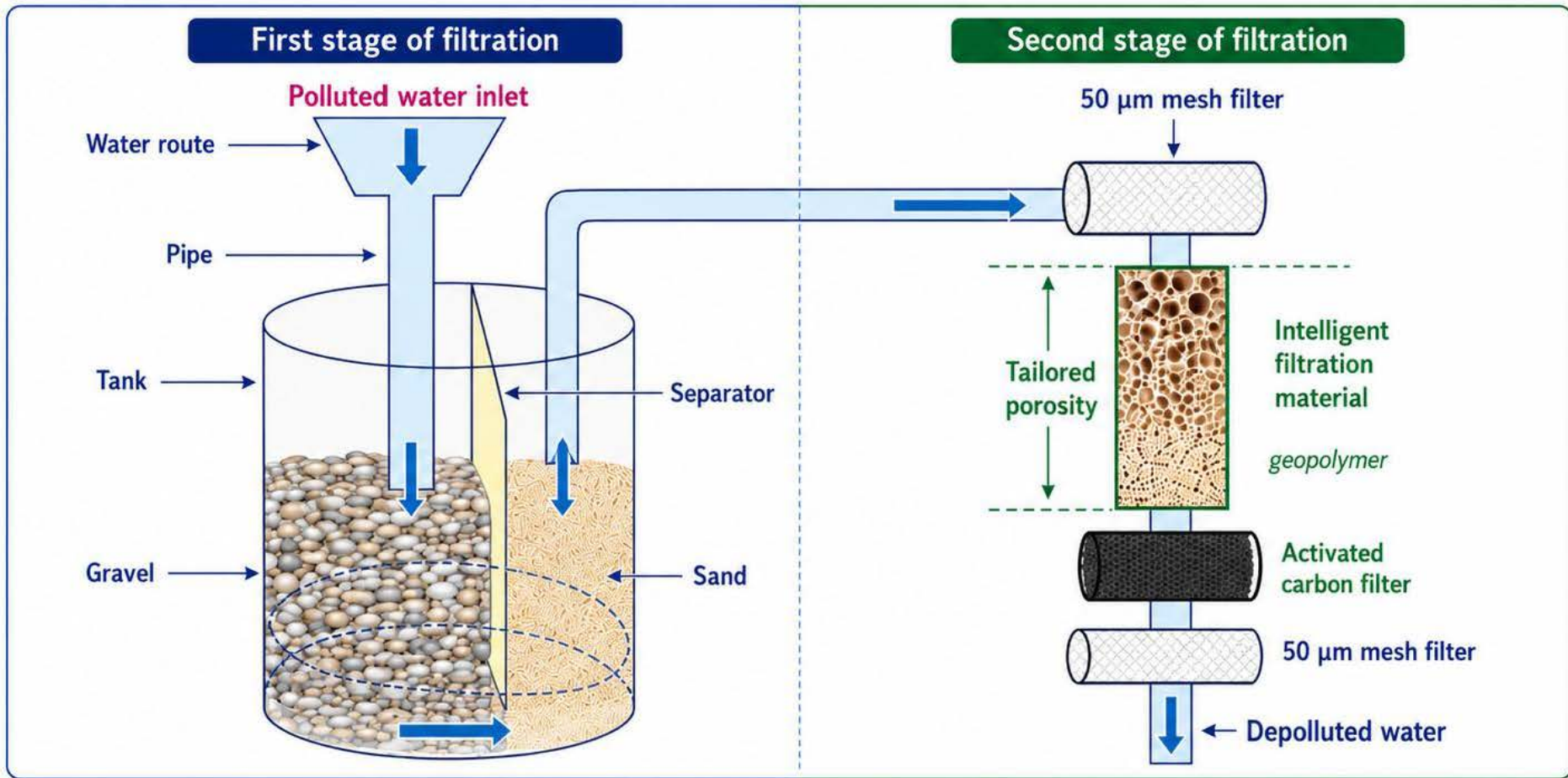
Black Sea coastal validation of the two-stage geopolymer-based filtration concept



Prototype tested in situ under Black Sea conditions.

21 Experimental filtration system and operating principle

Experimental two-stage filtration system including a carbon finishing step for Black Sea water treatment.



Stage 1 function

- Coarse filtration of large particles.
- Separation using gravel and sand media.
- Effective reduction of suspended solids and turbidity.



Stage 2 function

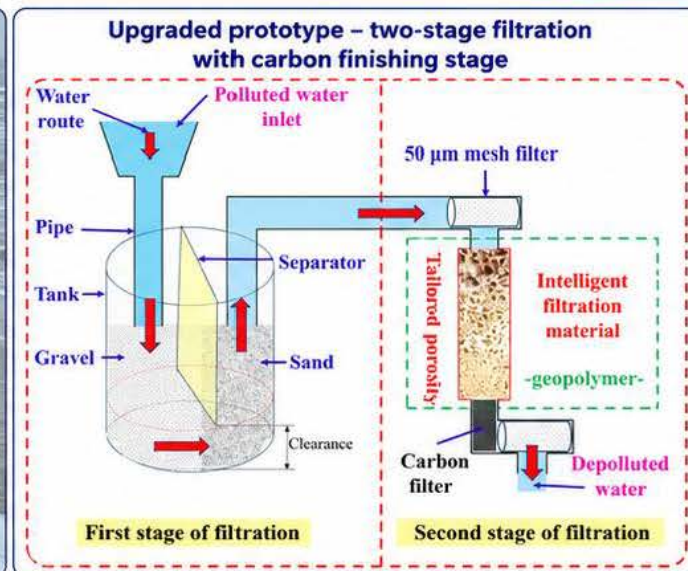
- 50 µm mesh filtration removes remaining fine particles.
- Geopolymer-based intelligent filtration with tailored porosity.
- Activated carbon polishing for organic contaminant reduction.



Operating principle

- Sequential treatment from polluted water inlet.
- Two complementary stages: physical filtration and adsorption.
- Depolluted water at the outlet.

Field testing of the two-stage filtration system including the carbon finishing stage



Second campaign confirmed the field operability of the upgraded system with carbon finishing stage.

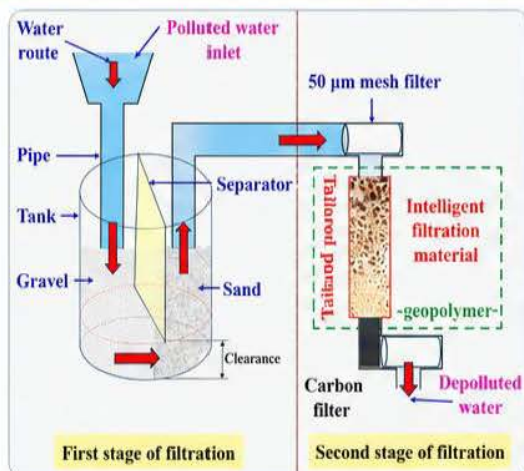


22 Main results: heavy metals reduction



On-site tests in the Black Sea (two field campaigns) demonstrated the high efficiency of the two-stage filtration system in reducing heavy metals concentrations.

Experimental setup – two-stage filtration system (with carbon finishing stage)



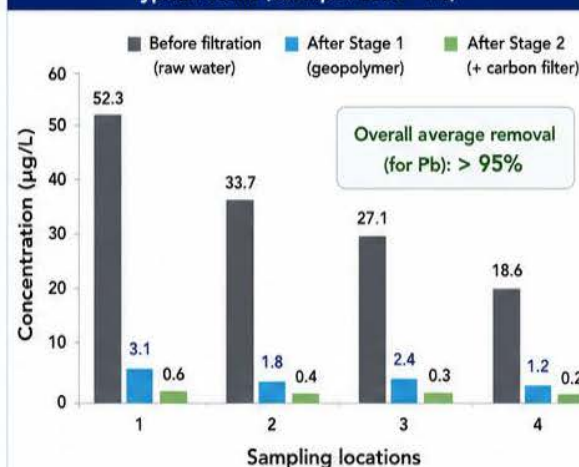
Sampling locations in the Black Sea



Heavy metals reduction – average removal efficiency (%)

Heavy metal	Average removal efficiency (%)		
	Campaign 1 (June 2025)	Campaign 2 (November 2025)	Overall average
Pb Lead	> 95%	> 95%	> 95%
Cd Cadmium	> 95%	> 95%	> 95%
Cu Copper	> 90%	> 93%	> 91.5%
Zn Zinc	> 90%	> 92%	> 91.0%
Cr Chromium	> 90%	> 91%	> 90.5%
Ni Nickel	> 90%	> 92%	> 91.0%
Fe Iron	> 85%	> 90%	> 87.5%

Typical results (example: Lead – Pb)



Key findings



Excellent heavy metals removal

The two-stage system consistently achieved > 85–95% average removal for all analyzed heavy metals across both campaigns.



Synergy of stages

Geopolymer captures and immobilizes metals via ion exchange, while the carbon stage polishes the water by removing residual metals and improving clarity.



Improved water quality

Filtered water meets stricter environmental standards for marine protection and potential reuse.



Sustainable solution

Using natural, low-cost materials (geopolymer + carbon) for an efficient and eco-friendly remediation approach.



The experimental results confirm the high efficiency of the two-stage filtration system in significantly reducing heavy metals in Black Sea water across different areas and during two field campaigns.



Main results: phosphates, petroleum hydrocarbons and nitrogen compounds

1 Phosphates (PO_4^{3-})



- ✓ Locations 1 and 2: reduced to non-detectable levels
- ✓ Location 3: 91.37% reduction
- ✓ Location 4: 89.36% reduction

Locations (downstream order)



Strong phosphate capture supports eutrophication mitigation.

2 Petroleum hydrocarbons

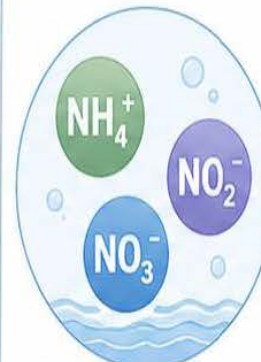


- ▮ Locations 1–3: up to 45.45% reduction in total petroleum hydrocarbons
- Location 4: unchanged, likely because the initial concentration was very low (0.03 mg/L)



The composite filter improved removal of the organic contaminant fraction.

3 Nitrogen compounds



- ✓ Promising reduction trend observed for NH_4^+ , NO_2^- and NO_3^-
- ✓ Performance depended on site-specific water composition



Potential contribution to lower nutrient loading and reduced eutrophication risk.



Tested configuration: metakaolin-based geopolymer composite with 20% zeolite aggregates; upgraded design included a carbon polishing stage.



- 1 Geopolymer–zeolite filtration improved nutrient and organic contaminant removal.



- 2 Removal efficiency depended on location and initial pollutant load.



- 3 The system shows promise for mixed marine contamination scenarios.

1

Turbidity



- ✓ Filtered water sometimes showed higher turbidity.
- ✓ This was attributed to the release of fine particles from the geopolymer filter.
- ✓ The carbon finishing stage was added downstream to capture entrained particles and improve water clarity.

2

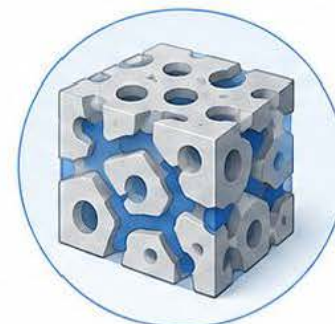
Iron release



- ✓ A slight increase in Fe content was observed in the analyzed samples.
- ✓ This behavior may be linked to the geopolymer matrix or the raw materials used.
- ✓ Low-iron precursors are recommended for future filter production.

3

Matrix stability



- ✓ The metakaolin-based geopolymer alone was not fully sufficient for complex marine pollution reduction.
- ✓ Stability and efficiency had to be improved for real marine conditions.
- ✓ Adding 20% zeolite aggregates created a more stable composite filtration material.



Design implications

These limitations guided the redesign of the system toward a geopolymer–zeolite composite and a downstream carbon polishing stage.

25 How to improve performance: composition, porosity and post-treatment

Optimization of the geopolymer material and operating conditions can further enhance filtration efficiency, extend service life and ensure long-term stability in the marine environment.



1. Composition optimization

Geopolymer base



Binders & activators



Additives

- Zeolite
- Activated carbon
- Iron oxides
- Biochar
- Nano-silica

Key levers



- ✓ Adjust binder ratio and activator concentration
- ✓ Incorporate functional additives for target contaminants
- ✓ Optimize granulometry and particle packing

2. Porosity and structure control

Tailored porosity for multi-contaminant removal



Macropores
(> 1 mm)
Hydraulic flow,
low head loss

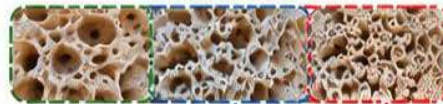


Mesopores
(10 nm – 1 µm)
Nutrients,
metals capture



Micropores
(< 10 nm)
Organics,
fine particle
retention

Target structure



High permeability

High adsorption

High retention



Key levers

- ✓ Control particle size distribution and compaction
- ✓ Tune geopolymerization temperature and curing time
- ✓ Balance porosity for flow and removal efficiency

3. Post-treatment and operation



Pre-filtration

- Use of coarse screen or sediment trap to reduce clogging and extend filter life.



Backwashing

- Periodic backwashing with clean sea water to restore permeability.



Post-treatment

- Disinfection (UV/chlorination) if needed for reuse applications.



Key levers



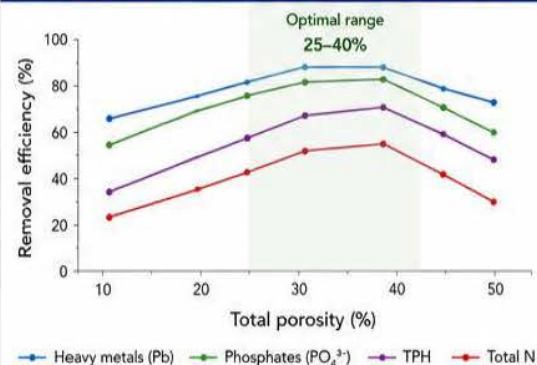
- ✓ Implement regular maintenance protocol
- ✓ Combine with disinfection for safe water reuse
- ✓ Monitor performance and schedule regeneration

Effect of composition on performance (examples)

Modification	Heavy metals removal (Pb)	Phosphates removal (PO ₄ ³⁻)	TPH removal	Hydraulic conductivity (m/h)
Reference	> 90%	> 80%	> 85%	1.2
+ Zeolite (10%)	> 95%	> 90%	> 90%	1.0
+ Activated carbon (10%)	> 95%	> 85%	> 95%	0.9
+ Nano-silica (5%)	> 95%	> 90%	> 92%	1.1
Optimized mix	> 95%	> 95%	> 95%	0.9–1.1

Values obtained from laboratory tests under steady-state conditions.

Influence of porosity on contaminants removal



Recommended improvement strategy



1. Tune composition

Select binder ratio and additives to target priority pollutants and mechanical stability.



2. Engineer porosity

Achieve a hierarchical pore structure for high removal efficiency with low head loss.



3. Apply post-treatment

Use pre-filtration, backwashing and disinfection to maintain performance and ensure safe reuse.



Synergy of material design and operation = maximum performance



By optimizing composition, controlling porosity and applying proper post-treatment, the two-stage filtration system can achieve higher efficiency, longer lifespan and broader applicability in marine conditions.

Optimized composition
(additives & binders)

Tailored porosity
(flow + retention)

Post-treatment
(pre-filtration,
backwash, disinfection)

Enhanced performance
(efficiency & durability)

Clean water
(safe & sustainable reuse)



Intelligent geopolymer-based filtration systems can be integrated into a wide range of coastal and port infrastructure for effective and sustainable pollution mitigation.

WHERE CAN THEY BE APPLIED?



Stormwater runoff treatment

Capture of suspended solids, metals, nutrients and hydrocarbons before discharge to the sea.



Port and harbor water treatment

Removal of pollutants from enclosed basins affected by ship traffic, maintenance and industrial activities.



Industrial and logistic areas

Treatment of wastewater, process water and contaminated runoff from industrial platforms.



Coastal protection structures

Integration in seawalls, revetments, breakwaters and drainage systems to control pollutant release.



Marinas and coastal communities

Decentralized solutions for small-scale applications and local water management.

EXAMPLES OF INTEGRATION IN INFRASTRUCTURE



Drainage channels

Pre-filtration using gravel and sand followed by geopolymer-based filter.



Along quay walls

Modular filtration units for water polishing in port basins.



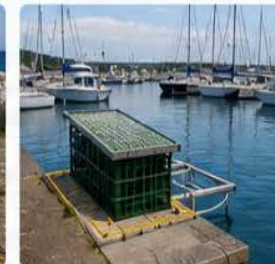
Industrial platforms

On-site treatment of contaminated water from industrial activities.



Coastal defense systems

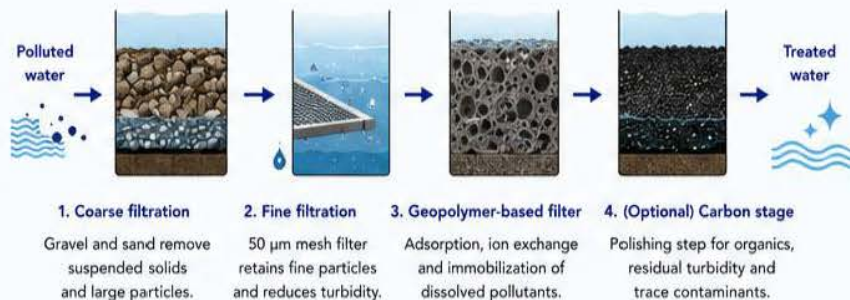
Installation within coastal structures for continuous water protection.



Floating or compact units

Adaptable solutions for marinas, small ports and tourist areas.

HOW IT WORKS IN REAL ENVIRONMENTS



KEY ADVANTAGES FOR COASTAL AND PORT AREAS

- ✓ **Effective pollutant removal**
Targets metals, nutrients, hydrocarbons, suspended solids and more.
- ✓ **Adaptable and modular**
Can be customized for different flow rates and site conditions.
- ✓ **Low carbon and sustainable**
Uses waste-derived materials and supports circular economy.
- ✓ **Durable and stable**
Resistant to marine environments, salinity and variable conditions.
- ✓ **Easy integration**
Can be integrated into existing infrastructure with minimal footprint.

POTENTIAL IMPACTS



Cleaner coastal and port waters



Protection of marine ecosystems



Reduced risks for human health



Support for sustainable port operations



Contribution to EU environmental goals



Intelligent geopolymer-based systems provide scalable, efficient and sustainable solutions for protecting coastal and port environments.

Intelligent geopolymer-based materials can be used to immobilize pollutants in contaminated sediments and as permeable reactive barriers (PRBs) to prevent their migration to the water column.

WHERE CAN THEY BE APPLIED?



Contaminated coastal sediments

Stabilization and immobilization of heavy metals, nutrients and organic pollutants.



Port and marina bed sediments

Control of pollutant release from sediments affected by shipping activities, fuels and maintenance.



Shoreline seepage zones

Interception of contaminated groundwater before it discharges into the sea.



Dredged material containment

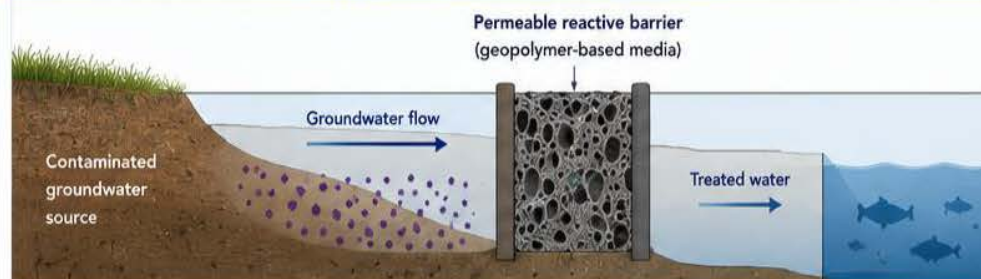
Use as reactive media in dredged material treatment cells or confined disposal facilities.



Wetlands and transition zones

Enhancement of natural attenuation processes and reduction of pollutant mobility.

PERMEABLE REACTIVE BARRIER (PRB) CONCEPT



Adsorption

Pollutants attach to active surface sites.



Ion exchange

Exchangeable ions capture contaminants.



Precipitation

Pollutants converted to insoluble compounds.



Immobilization

Pollutants locked inside the geopolymer matrix.



Filtration

Suspended particles are retained.

SUITABLE POLLUTANTS



Heavy metals

- Lead, cadmium, copper, zinc, nickel, chromium, etc.



Nutrients

- Phosphates, ammonium, nitrates, nitrites.



Hydrocarbons

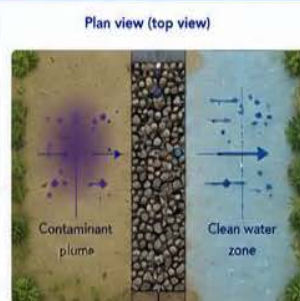
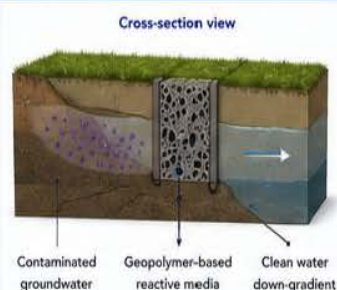
- Oil products, PAHs, fuel residues.



Other contaminants

- Organic compounds, phenols, emerging contaminants.

PRB CONFIGURATIONS



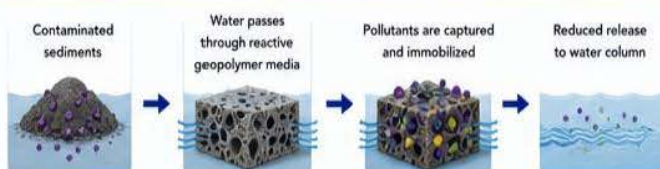
Typical placement

- Perpendicular to groundwater flow
- Across contaminant plume pathways
- Up-gradient of sensitive receivers (sea, lagoons, drinking water sources)

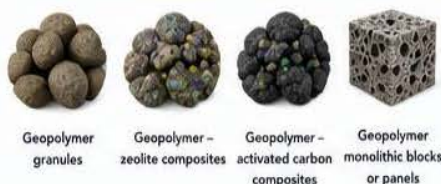
KEY ADVANTAGES

- ✓ **Passive and sustainable solution**
Works without external energy.
- ✓ **Long-term immobilization**
Reduces pollutant mobility and bioavailability.
- ✓ **Adaptable and cost-effective**
Can be customized for different sites and contaminants.
- ✓ **Low environmental footprint**
Uses waste-derived materials and supports circular economy.
- ✓ **Enhances natural attenuation**
Supports in-situ remediation processes.

HOW IT WORKS IN SEDIMENTS



MATERIALS OPTIONS



EXAMPLE APPLICATION SCENARIO



Geopolymer-based materials offer a reliable, durable and sustainable approach for sediments remediation and for creating permeable reactive barriers that protect marine environments by preventing pollutant migration and supporting ecosystem recovery.



Smart materials for cleaner seas and resilient coastal communities.

Applications for sediments and permeable reactive barriers

Where these applications fit



Contaminated coastal sediments



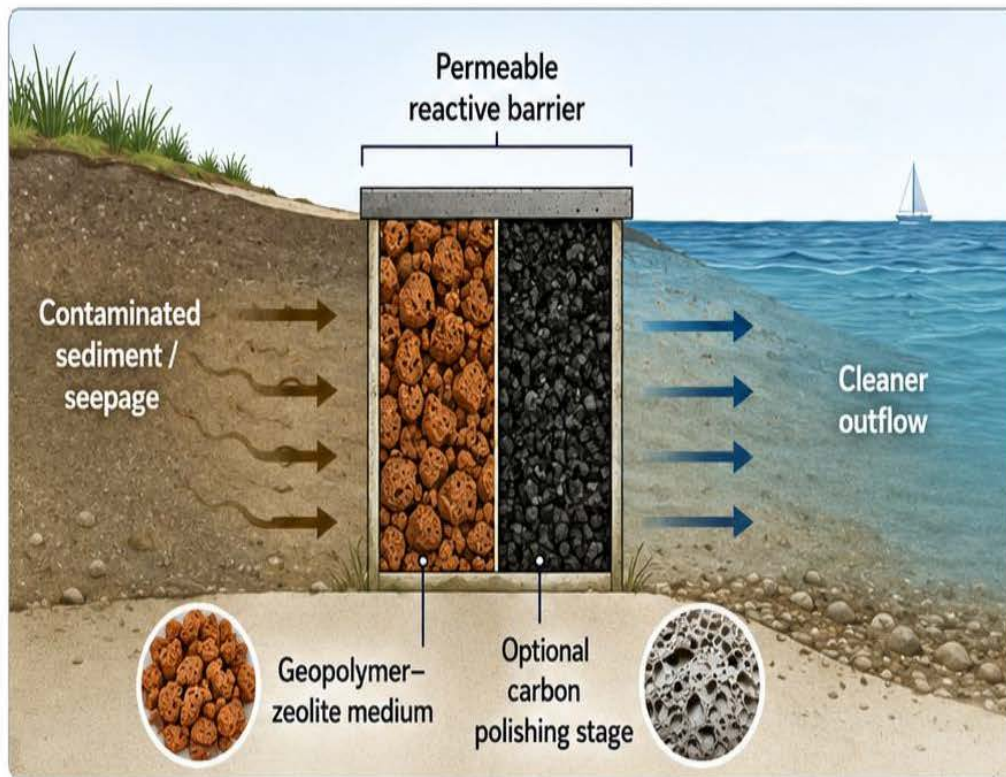
Port and marina sediment hotspots



Shoreline seepage / runoff interception



Dredged-material or confined treatment cells



Key functions

- Metal immobilization
- Reduction of hydrocarbon mobility
- Nutrient attenuation
- Passive in-situ treatment
- Modular and low-cost deployment

Why it matters

Geopolymer-based reactive barriers can passively reduce contaminant migration from sediments to coastal waters while supporting low-cost and scalable remediation.



Circular economy: waste-derived precursors and spent filter reuse

Closing the loop for sustainable marine filtration materials

1 Waste-derived precursors

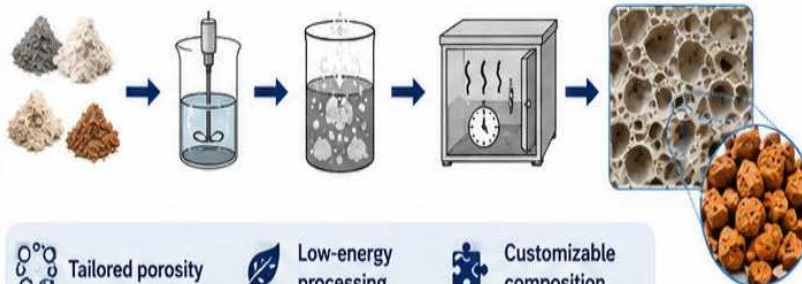
Metakaolin or fly ash Zeolite / natural minerals Expanded clay / ceramic waste Construction / demolition waste



- Local/low-cost resources
- Waste valorization
- Reduced raw-material demand

2 Filter production

Precursor selection Alkaline activation Shaping / foaming Curing Porous geopolymer filter



- Tailored porosity
- Low-energy processing
- Customizable composition

3 Use in filtration

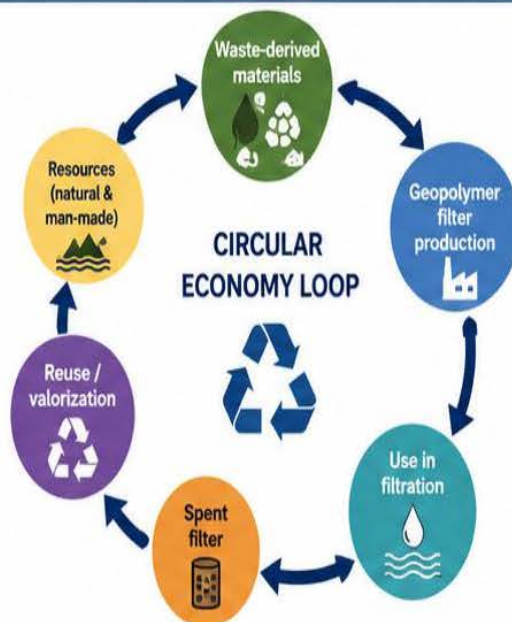
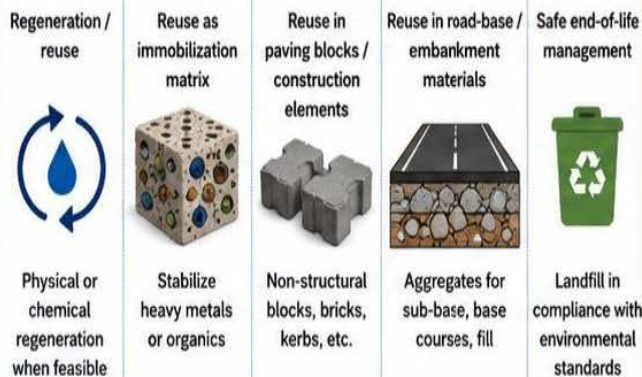


Targets a range of pollutants:

- Nutrients (e.g., N, P)
- Heavy metals (e.g., Pb, Cu, Zn)
- Hydrocarbons
- Organic contaminants

4 Spent filter management & reuse

After service life, multiple pathways to keep materials in use



Benefits of the circular approach

- Resource efficiency
- Lower environmental footprint
- Reduced waste disposal
- Support for circular economy



Life-cycle safety and environmental risks

Key safety considerations for geopolymer-based marine filtration systems

1. Raw materials and production

Metakaolin or aluminosilicate precursor Porous expanded clay / ceramic granules Alkaline activator



Main risks

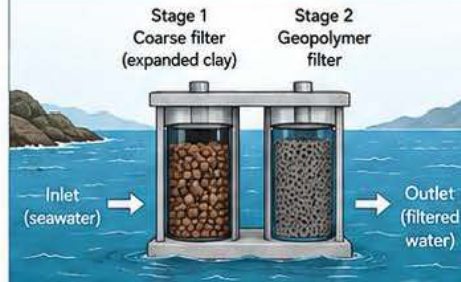
- Dust exposure during powder handling
- Corrosive alkaline solutions
- Energy and water use during processing



Control measures

- PPE, closed handling where possible
- Proper storage
- Optimized mix design

2. Deployment and operation



Main risks

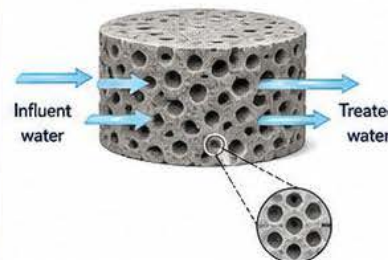
- Temporary turbidity increase during installation
- Variable salinity and pH in marine water
- Clogging or hydraulic instability
- Biofouling with long-term use



Control measures

- Pre-rinsing
- Gradual start-up
- Periodic inspection and cleaning
- Stable housing

3. Performance and matrix stability



Main risks

- Possible iron release or minor leaching under aggressive conditions
- Performance loss due to saturation
- Release of captured contaminants if the matrix is damaged



Control measures

- Optimized composition
- Controlled porosity
- Sufficient curing
- Monitoring of effluent quality

4. Spent filter and end-of-life



Main risks

- Contaminated spent media
- Improper disposal
- Re-suspension of captured pollutants during handling



Control measures

- Stabilization/solidification
- Reuse only when safe
- Controlled collection and disposal
- Documentation and traceability

5. Key monitoring parameters



pH



Salinity



Turbidity



Conductivity



Nutrients
(N, P)



Heavy metals
(e.g., Fe, Zn, Pb)



Hydrocarbons
(TPH, PAHs)



Flow rate



Visual integrity
of the filter

Life-cycle flow (simplified)



Main environmental risk categories



Worker
safety



Leaching
risk



Marine-water
quality impact



End-of-life
management

Core message



Safety must be evaluated across the full life cycle. With proper formulation, monitoring and end-of-life management, geopolymer-based systems can offer low-risk and sustainable marine remediation.

30 Integration with digital monitoring and smart systems



The two-stage geopolymer + carbon filtration system is enhanced by digital technologies for real-time monitoring, data-driven decisions and efficient operations in marine environments.

1. Smart sensing for water quality monitoring

Multi-parameter sensors

- pH
- Turbidity
- Conductivity / Salinity
- Dissolved oxygen
- Temperature
- ORP
- Nutrients (e.g., NO_3^- , PO_4^{3-})
- Heavy metals (online/ISE)



Real-time data acquisition every few minutes and transmission to cloud platform

2. Aerial & satellite surveillance for hotspot detection

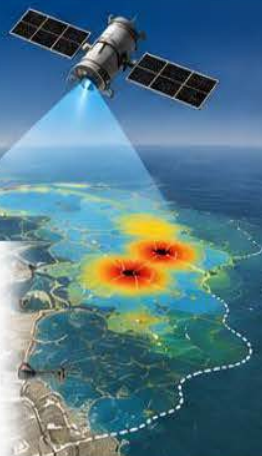
Satellite monitoring

- Detects large-scale changes: oil slicks, plumes, turbidity, temperature anomalies
- SAR & multispectral data identify potential pollution hotspots
- Historical trends & seasonal patterns



Drone missions

- Rapid assessment of hotspots
- High-resolution imaging & water sampling
- Guidance for filter deployment & verification



3. Data platform, analytics & decision support

Cloud dashboard



Key capabilities

- Real-time visualization & alerts
- Trend analysis & prediction
- Automated reporting
- Decision support for deployment
- Data integration (sensors, drones, satellites, models)

Secure data storage, user access management & cybersecurity

4. Automated deployment & operation

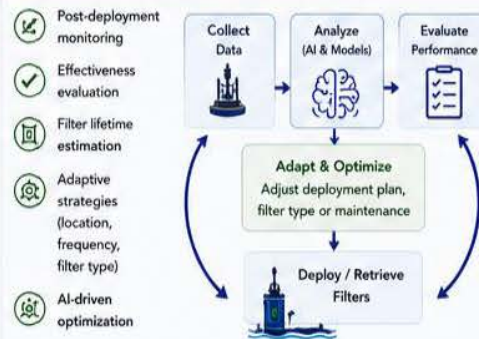
Autonomous / assisted platforms

- USVs / boats / drones for filter transport
- Precise positioning & navigation
- Pre-programmed missions
- Minimized human intervention

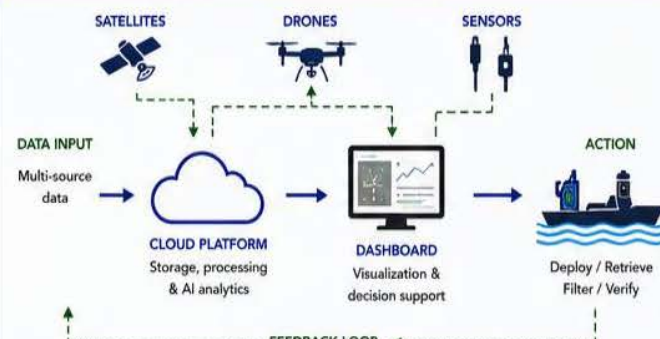


- GPS & RTK positioning
- Obstacle avoidance
- Battery & health monitoring
- Safe operations in harsh conditions

5. Verify, evaluate & adapt



6. System architecture overview



Key benefits

- Targeted deployment (right place, right time)
- Efficient resource use & cost savings
- Faster response to pollution incidents
- Higher filtration performance & system reliability
- Better environmental outcomes & transparency
- Supports sustainable & resilient marine management

From monitoring to action: the smart filtration cycle



By integrating sensors, drones, satellites and intelligent analytics, the two-stage geopolymer + carbon filtration system becomes a smart, adaptive and highly effective solution for protecting marine environments and responding rapidly to pollution hotspots.



Smart systems for cleaner seas and resilient communities.

31 Research gaps and future validation in real marine conditions



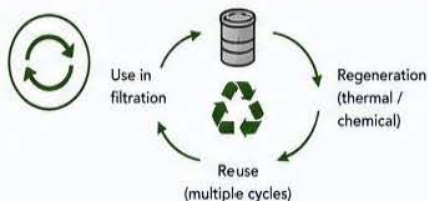
Further studies and long-term validations are required to ensure the reliability, scalability and environmental sustainability of the two-stage geopolymer + carbon filtration system.

1. Long-term durability & stability



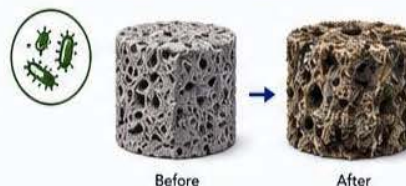
- Assess structural and chemical stability under prolonged exposure to seawater.
- Evaluate mechanical strength retention, dissolution, and phase changes.
- Investigate performance over seasonal variations and extreme conditions.

2. Repeated use, regeneration & lifecycle



- Optimize regeneration methods with minimal loss of performance.
- Determine practical number of cycles.
- Develop criteria for safe end-of-life.

3. Biofouling and biological interactions



- Evaluate biofouling development on filter surfaces.
- Assess impact on flow, adsorption and filtration efficiency.
- Investigate eco-friendly anti-fouling strategies.

4. Performance on complex contamination



- Validate efficiency for diverse and mixed pollutants (metals, organics, nutrients, microplastics).
- Study competitive adsorption and synergistic effects.
- Evaluate performance under variable pH, salinity, turbidity and organic load.

5. Real marine environment validation



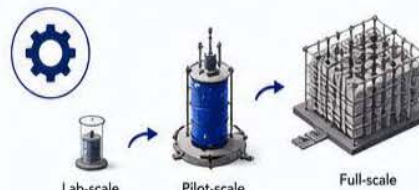
- Conduct pilot-scale trials in coastal, port and offshore areas.
- Compare performance with lab results.
- Monitor under dynamic conditions (waves, currents, temperature fluctuations).

6. Environmental impact & ecotoxicology



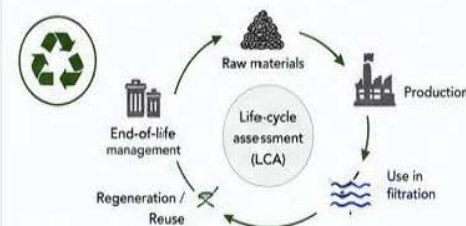
- Assess potential leaching of elements (e.g., Na, Al, Si, Fe).
- Evaluate impacts on marine organisms and ecosystems.
- Confirm safety of the spent filter and by-products.

7. Scale-up, engineering & operational challenges



- Optimize hydraulic design and flow management.
- Develop modular, scalable and cost-effective systems.
- Address challenges in deployment, maintenance and retrieval.

8. Life-cycle assessment & circularity



- Perform comprehensive LCA for environmental footprint.
- Quantify benefits vs. conventional technologies.
- Optimize circular strategies for materials and spent filters.

Key research needs



Long-term field data under real conditions



Standardized testing protocols for marine systems



Performance vs. cost and scalability analysis

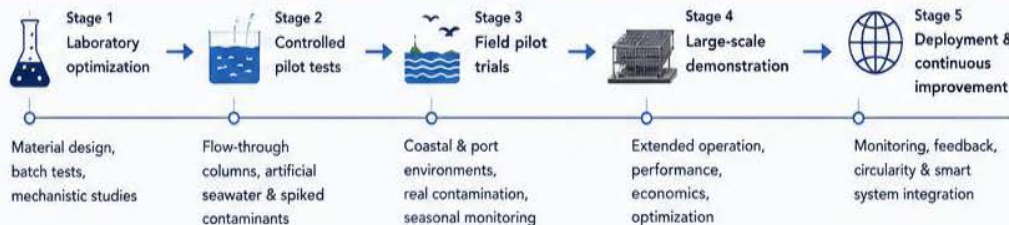


Ecological safety and sustainability validation



Integration with monitoring and smart systems

Future validation roadmap



Bridging these research gaps through systematic validation in real marine conditions will ensure that the two-stage geopolymer + carbon filtration system is safe, effective, scalable and ready for real-world marine pollution mitigation.



Reliable & safe



Sustainable & circular



Scalable & efficient



Impactful for cleaner seas

Intelligent geopolymer-based materials can support sustainable marine pollution mitigation



Filtration

Efficient removal of particles and suspended matter.



Adsorption

Capture of dissolved pollutants, heavy metals and organics.



Immobilization

Stabilization of contaminants within a robust, durable geopolymer matrix.



Circular economy

Use of waste-derived precursors and responsible management of spent filters.



Thank you
for your attention!

Q&A ?

A holistic, future-ready approach



Protecting
marine ecosystems



Safeguarding
human health



Supporting sustainable
blue economy



Enabling data-driven
decisions and smart
operations



By combining advanced materials, green chemistry, circular economy and digital intelligence, we can build cleaner seas and a more resilient future for our planet.

