



International
Organization
for
Chemical Sciences
in Development



YOUNG VOICES IN THE CHEMICAL SCIENCES FOR SUSTAINABILITY 2026

**Winners and Finalists in the IOCD Essay Competition
sponsored by the Royal Society of Chemistry**

**How can the chemical sciences
ensure sustainable access to
clean water for all needs?**

Editors: Stephen A. Matlin, Federico Rosei, Philippe Lambin, Seamus Delaney and Lei Jin

International Organization for Chemical Sciences in Development
Namur
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**Young Voices in the Chemical Sciences for Sustainability 2026
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Introduction

Stephen A. Matlin, Federico Rosei, Philippe Lambin, Seamus Delaney and Lei Jin

International Organization for Chemical Sciences in Development (IOCD), Namur

Background

IOCD promotes the pursuit and application of the chemical sciences for sustainable, equitable human development and economic growth, working to reposition chemistry as a science for the benefit of society and promote the role of the chemical sciences in sustainable development. IOCD's action groups cover a range of strategically chosen activities to advance this mission (Box 1).

Box 1 IOCD action groups¹

Materials for Energy Conversion, Saving and Storage (MATECSS)² is led by IOCD's Executive Director Federico Rosei. The group seeks to facilitate technology transfer by connecting experts from around the world with local scientists, engineers and students in low-and middle-income countries, and to foster development of low cost, adaptive technologies based on energy materials appropriate for local-scale energy systems and that use local resources.

Chemists for Sustainability (C4S)³ is an international group of chemists providing advocacy and think-tank roles through written articles, lectures at various fora and web materials,⁴ building the case for chemistry's central contributions to sustainable development.

Green and Sustainable Electronics (GSE) is a Working Group led by Teresa Cechi in Fermo, Italy, in collaboration with Clara Santato who holds the UNESCO Chair in GSE at Polytechnique Montreal in Canada.⁵ The group focuses on the growing environmental burden of waste electronic and electrical equipment, collaborates with Sub-Saharan countries that have been considered e-waste dumping sites, for recovery, upcycling efforts and eco-design.

The **Chemistry Education Working Group** makes the case for reorientation of the curriculum to enable it to better serve the needs of society to understand and tackle the unfolding global crises of the 21st century.⁶ In collaboration with the International Union of Pure and Applied Chemistry, IOCD has contributed to the leadership of global projects to help embed systems thinking in chemistry education⁷ and to engage with chemical industry on systems thinking and sustainability.⁸

As part of its strategy, IOCD seeks to stimulate young people to develop their roles in reshaping chemistry as a core sustainability science – including through encouraging them to write about the subject. In 2023, IOCD launched an annual Essay Competition, **Young Voices in the Chemical Sciences for Sustainability**.⁹

The competition, organized and managed by IOCD, to highlight the roles of the chemical sciences in promoting sustainability and to encourage young people (aged under 35 on the annual closing date) to explore the relevance of scientific approaches to tackling sustainability challenges and provide them with an opportunity to present their perspectives. The competition is sponsored by the Royal Society of Chemistry, a leading voice for the chemical sciences and their role in sustainability.¹⁰

Essays that are very highly rated in the judging process are selected as Finalists, from which the Regional Winners are identified, with regions being defined according to the World Bank's current geographic classification.¹¹ Regional Winners each receive a prize of US\$ 500 and a Winner's Certificate, and their essays are published in the journal *RSC Sustainability*. Entrants whose essays are selected as Finalists also receive a Winner's Certificate, and their essays are published in an annual IOCD Compendium online.

The results of the annual competitions since 2023 can be found on IOCD's website.¹²

Results of the 2026 competition

The theme of the 2026 IOCD Essay Competition was **How can the chemical sciences ensure sustainable access to clean water for all needs?**^{13,14} From over 200 entries, evaluation by volunteers from around the world recruited by IOCD provided a short-list of about 70 essays for further assessment, which led to 38 being selected as Finalists. These were then grouped by region¹¹ for judging the Regional Winners. Six essays designated as 2026 Regional Winners were published¹⁵ online in October 2026 and included in the 2026 issue 11 of *RSC Sustainability* as detailed below. Essays from the 32 additional Finalists in the 2026 competition are published in this compendium, available on IOCD's website (<https://www.iocd.org>).

The issue of stewarding clean water resources is arising in different ways across the globe and poses tremendous societal challenges almost everywhere. The entries submitted to the competition illustrate how young people view the role that chemistry can play in addressing these challenges. In their essays, the finalists discussed a variety of chemical issues related to ensuring long-term access to clean water. They have identified

many sources of pollution that require specific actions. Recognising that prevention is better than cure, some authors suggested ways to reduce the water consumption in agricultural and industrial processes or in cooling systems, as well as reduce the contaminant generation. Others emphasised the importance of designing sensors that respond quickly in order to detect water pollution early and treat its effects efficiently. Aside from traditional water purification techniques such as filtration, flocculation, chlorination and reverse osmosis, the essays described new approaches based on advanced materials, including nanofiltration using nanoporous membranes, the adsorption of pollutants using metal-organic frameworks, and the destruction of organic compounds and pharmaceuticals using photocatalysis. While solutions to the circularity of water resources exist at laboratory level, much remains to be done to scale up these solutions to deliver real-world applications.

We are extremely grateful to the Royal Society of Chemistry for sponsoring this competition, through providing financial support to help cover the costs of operations and by participating in the competition process and publication of the Regional Winner essays. We are also extremely appreciative of the work of the dozens of volunteer evaluators from around the world, who assist us in reviewing the entries and selecting the Finalists and Winners. Most of all, we greatly appreciate the efforts made by young people around the world to write fascinating essays and to submit them for our scrutiny.

IOCD will continue to operate this annual Essay Competition, *Young Voices in the Chemical Sciences for Sustainability*, offering each year a new topic on which young people can express their perspectives. Members of the chemistry community of all ages are invited to join us – whether as entrants, evaluators or promoters of the competition. Further information can be found on IOCD’s website (<https://www.iocd.org>), or by writing to essay@iocd.org.

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Regional Winners

Regional Winner East Asia and Pacific

Chemistry before crisis: reframing the role of chemical sciences in sustainable water systems

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Muhammad Sarkawi, from Indonesia, begins by recognising that ensuring sustainable access to clean water is both a technological challenge and a question of the timing at which chemistry is applied: chemical interventions should preferably not happen after pollution has occurred and ecological imbalances have already developed. He argues that the role of chemistry must shift from reactive removal to proactive material stewardship, intervening early to maintain equilibrium and restore nutrient circulation before ecological crises occur. Using the case of phosphorus to illustrate his argument, Sarkawi notes that the biogeochemical flow of P greatly exceeds the safe operating limit identified in the Planetary Boundaries framework and the existing response exemplifies a broader paradigm in environmental chemistry – one which prioritizes remediation after imbalance rather than prevention before crisis. The essay discusses chemistry-based approaches to earlier, preventive interventions, emphasising the importance of rapid chemical sensing for the early identification of sources of problems. Sarkawi also goes on to discuss remediation approaches that can enable the reintegration of treated wastewaters into clean water supplies, highlighting the promising role of metal-organic frameworks (MOFs) as highly selective and efficient adsorbents. Importantly, these materials are regenerable and the recovery of phosphates can contribute to their circularity in use as fertilizers.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90060G>

Regional Winner Europe and Central Asia

From treatment to reuse: how chemical sciences transform the water cycle

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Miguel-Jorge Reig-Valor (⁷ from Spain, discusses the achievement of sustainable, clean water supplies through implementing circular water systems. This demands rethinking how we treat, recover, and manage this chemical resource, whose availability in a sufficiently pure form for human use is affected by the accumulation, transformation, and persistence of contaminants. A comprehensive approach rests on analytical chemistry foundations enabling detection and characterization of the many and growing types of pollutants affecting water supplies. Reig-Valor highlights recent advances in materials science that are significantly enhancing the performance of separation technologies to purify water, as well as advanced oxidation processes (AOPs) which generate highly reactive species such as hydroxyl or sulfate radicals, as well as photocatalysis, especially under solar irradiation. These approaches can efficiently degrade high proportions of a wide range of contaminants, including persistent organics such as pesticides, pharmaceuticals, and phenolic derivatives. A number of barriers to achieving the ideal of circularity of the water itself and the contaminants it carries are identified. These include cost factors, scaling laboratory innovations to industrial practice, and the influence of social and political factors. Decentralized treatment systems, supported by digitalization, low-cost sensors and advanced control strategies signpost one way forward, especially for rural or low-infrastructure regions.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90061E>

Regional Winner
Latin America and the Caribbean

***Water recovery from an underground sea:
membrane distillation crystallization for
zero liquid discharge in lithium mining***

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Diego Mirabal Castillo, from Cuba, illustrates the potential for operation of a circular water model by focusing on the case of lithium mining in the Lithium Triangle region in the Altiplano-Puna plateau which spans the borders of Argentina, Bolivia, and Chile. There, a vast 'underground sea' stores a chemically complex brine which accounts for approximately 60% of known global Li resources. In this arid region, the large losses of water by evaporation during Li extraction add to the scarcity of water, which is also a very important resource for the local ecosystems and indigenous inhabitants. The essay explains how a circular approach, involving membrane distillation crystallisation (MDCr) in Li mining, can enable a desalination process that also recovers up to 95% of the brine's water content, while reducing the brine processing time from nearly 24 months in solar evaporation ponds to just a few days and operating at a significantly lower temperature. The potential integration of solar-powered technologies to heat the brine can also significantly reduce specific energy consumption and facilitate recover of other salts present, such as NaCl. Successful industrial scale-up of MDCr systems might also provide recovered water for further purification for local agriculture, livestock, and potentially human consumption.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90062C>

Regional Winner
Middle East and North Africa

***From lab to tap: scalable self-powered chemical systems
for universal clean water access***

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Muhammad Madni, from Pakistan, reflects that, while nearly one in three people worldwide lack access to safe drinking water, conventional technologies such as distillation, reverse osmosis, and chlorination have enabled large-scale purification – but they remain energy-intensive and logistically inaccessible to those who need them most. His essay concentrates on addressing this challenge through a transition toward decentralized, self-powered chemical systems that operate directly at the point of use. These rely on catalytic approaches operating at the molecular level, enabling the degradation of pollutants and inactivation of pathogens through reactive intermediates such as the reactive oxygen species generated by AOPs. However, while most AOPs depend on external energy sources such as ultraviolet irradiation or electrical input, limiting their application in resource-constrained environments, a different approach harnesses naturally available energy sources such as sunlight and mechanical motion. Piezocatalysis makes use of induced charge separation in piezoelectric materials with non-centrosymmetric crystal structures, developing a piezoelectric potential which drives redox reactions at the material surface. Piezocatalysis operates continuously under naturally available mechanical forces, making it particularly suitable for decentralized applications in flowing water systems, pipelines, and natural water bodies. Madni envisions a hybrid purification platform that integrates piezoelectric materials with carbon dot-based sensing and catalytic functionalities.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90063A>

**Regional Winner
South Asia**

***Think small, impact large: how nanochemistry
changes the fate of wastewater***

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Saibalendu Sarkar (South Asia),¹⁰ from India, observes that the greatest challenge of the 21st century is not finding new sources, of clean water, but learning to reuse what we already have – reimagining Sustainable Development Goal (SDG) 6 beyond the provision of clean water toward an integrated framework embracing wastewater treatment (WWT), safe water reuse, ecological restoration, resource recovery, and equitable water governance. Nanochemistry offers a powerful platform for pollutant removal, resource recovery and sustainable water reuse, thereby advancing the four pillars of the circular economy – reduce, reuse, recycle, and recover. It affords a spectrum of applications in WWT through adsorption, nanofiltration, photocatalysis, and disinfection, with recent advances in materials such as graphene, MOFs and MXenes enabling high water flux, superior ion rejection and improved resistance to nanoporous membrane swelling. The WWT strategy also incorporates photocatalysis, using nanostructures used to enhance light absorption and charge separation, leading to improved degradation of pollutants, removal of dyes, disinfection of bacteria and lower nitrate levels. The essay notes that the global water and WWT market is projected to grow rapidly, reaching \$515.8 billion by 2028, affording a pathway to socio-economic gains that align with several SDGs. However, significant barriers to large-scale implementation, include economic, technical, environmental, and regulatory challenges.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90064J>

**Regional Winner
Sub-Saharan Africa**

***The Angstrom gatekeeper: decoupling water security
from fossil energy via adaptive nanomaterials***

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Ikenna Sebastian Okechukwu (Sub-Saharan Africa),¹¹ from Nigeria, stresses the potential of adaptive nanomaterials in helping to decouple water security from fossil energy. He characterises the traditional approaches to water purification, such as reverse osmosis, as “outdated brute-force methods” that create an unsustainable water-energy nexus in which treating water requires energy, while generating energy frequently requires water. The solution offered involves rethinking molecular separation, employing highly selective barriers built from adaptive nanomaterials that act like molecular-scale gates. Conventional methods for removing organic pollutants are also criticised, since they do not destroy the pollutants but transfer them to the adsorbent (e.g. carbon) whose disposal contributes significantly to greenhouse gas emissions and environmental pollution. Okechukwu describes two “hero systems” to overcome these challenges, one of which is to employ adaptive nanomaterials such as MOFs in membranes tailored to meet local requirements for separation while requiring much milder conditions and less energy. His second hero system addresses the problem of “forever chemicals” in water sources through degradation employing nanoscale electrocatalysts. While the two systems offer the potential to purify water under ambient conditions and facilitate water circularity, the challenges of scalability, safety, policy, and circularity that need to be overcome to move them from laboratory to widespread use are also discussed.

Article at: *RSC Sustainability*, 2026, <https://doi.org/10.1039/D6SU90065H>

Regional Winners

Finalist

No test, no trust: knowing what's in the water

Ayush AGARWAL

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A good doctor does not prescribe blindly. Before treatment comes diagnosis. A patient is examined, tests are ordered, results are interpreted, and only then is the therapy chosen. If the test is inaccurate, the patient may be treated for the wrong disease. If it is imprecise, the doctor may not know whether a change is real or accidental. If it is unreliable, the same sample may tell a different story in different clinics. In medicine, a poor diagnosis can harm one life. In water management, poor diagnosis can harm whole communities.

This matters because water is not just another resource. It is woven into health, food production, industry, ecosystems, and dignity. In South Asia, the phrase *"Jal hai to jeewan hai"* captures a simple truth: if there is water, there is life. Even beyond Earth, water is one of the first signs we seek when asking whether a planet could harbour life. Yet on Earth, where the need is immediate and undeniable, clean water is still too often discussed only in terms of treatment plants, filters, pipelines, or desalination units. These are essential, but they come after a more basic question. What exactly does water contain, where is it found, in what concentration, and with what confidence do we know it?

Sustainable access to clean water begins with the chemical sciences answering that question well. Before water can be purified, allocated, reused, or regulated, it must be measured accurately, precisely and affordably. In that sense, diagnosis is the first intervention.

The importance of correct measurement is often underestimated because it is less visible than treatment. A membrane, a chlorination unit, or a desalination plant looks like action. A calibrated instrument, a validated method, or a carefully collected sample may seem secondary. But without trustworthy analysis, even the most advanced treatment can become guesswork! Arsenic,¹ nitrate,² fluoride,³ lead,⁴ pesticides,⁵ pharmaceuticals,⁶ microplastics,⁷ and other contaminants^{8,9} do not announce themselves clearly to the eye. Some are harmful even at trace levels. Others change their chemical properties depending on pH, redox conditions, or interactions with natural organic matter.^{10–12} For example, two water samples may contain the same element but pose different risks because the chemistry of speciation changes toxicity, mobility, and treatability. Measuring total concentration alone is not always enough.

Here, analytical chemistry becomes central, both to understanding water composition and to evaluating how effectively treatment systems remove pollutants. This role rests on the three fundamental pillars of measurement: accuracy, precision, and reliability. Accuracy asks whether a measurement is close to the true value. Precision asks whether repeated measurements agree with one another. Reliability asks whether a method remains dependable across operators, locations, water matrices, and time. These are not abstract laboratory ideals. They determine whether a village well is declared safe or unsafe, whether a treatment system is correctly selected, and whether policymakers view contamination as an isolated event or a chronic pattern.

Consider the doctor again. A test that misses disease leads to false reassurance. A test that exaggerates disease leads to unnecessary treatment, cost, and anxiety. Water systems face the same dangers. A false negative can leave a community exposed to toxic metals or microbial contamination. A false positive can divert scarce resources towards the wrong source, the wrong contaminant, or the wrong technology. In regions where financial and technical capacity is limited, the cost of measurement error is amplified because every wrong decision consumes money, time and public trust that may not be easily recovered.

This is why the chemical sciences are indispensable. They do not simply produce numbers. They determine which analytes matter, how they can be separated, how low they can be detected, which interferences must be controlled, and how results should be interpreted in the real world rather than in an idealised laboratory matrix. Spectroscopy,^{13,14} chromatography,¹⁵ mass spectrometry,^{16,17} electrochemistry,¹⁸ biosensing,^{19–21} and microfluidics,^{22,23} each offer different information. High-performance laboratory methods can identify contaminants with excellent sensitivity and specificity. Portable electrochemical and optical sensors can bring testing closer to the point of need.^{24,25} Paper-based and microfluidic devices can reduce reagent use, cost and

turnaround time.^{26,27} Smart sensor systems and smartphone-assisted readouts can help extend monitoring into settings where centralised laboratories are scarce.^{28,29}

But the goal is not to replace rigorous analysis with cheap approximation. It is to build a layered system in which methods are fit for purpose. A central laboratory may be necessary for confirmatory analysis, speciation, and trace quantification. A field sensor may be best for screening, surveillance, and rapid response.²⁴ The chemical sciences are uniquely positioned to connect these levels by designing methods that are not only sensitive and selective, but also robust, reproducible, and usable outside highly controlled environment.³⁰

This is harder than it sounds because real water is chemically complex. It contains suspended solids, salts, natural organic matter, fluctuating pH, biological activity, and seasonal variation. These factors create matrix effects that can distort signals, suppress sensitivity, or produce misleading readings.³¹ A sensor that performs beautifully in deionised water may fail in ground water, wastewater or a river downstream of agriculture or industry. Sustainable access to clean water therefore depends not only on clever sensors, but also on validating them against the messiness of actual water systems.

Once this is understood, measurement becomes more than a technical issue. It becomes a matter of justice. Communities that are not monitored can become communities that are not protected. Contamination that is not measured can remain politically invisible. In practice, inequality in water access is often mirrored by inequality in analytical capacity. Wealthier systems can afford regular surveillance, certified laboratories, quality control and timely reporting. Poorer or remote systems may depend on sporadic sampling, outdated methods, or no monitoring at all. The burden of uncertainty then falls most heavily on those least able to bear it.

This is why water measurement also matters for sustainable development more broadly. At the centre are the Sustainable Development Goals (SDGs), especially SDG 6, which calls for clean water and sanitation for all. But water analysis also supports SDG 3 on health by identifying contaminants before disease spreads, SDG 2 on food security by guiding safe irrigation and nutrient management, SDG 12 on responsible production and consumption by enabling wastewater reuse and pollution control, and SDG 14 by helping prevent chemical contamination of aquatic ecosystems.³² The SDGs are not achieved by aspirations alone. They depend on evidence. A community cannot claim safe access if the chemistry of its water is unknown or poorly characterised. A treatment technology cannot be called sustainable if it is not matched to the contaminants actually present. A reuse system cannot be trusted if safety is assumed rather than demonstrated.

For this reason, the future contributions of the chemical sciences must be two-fold. First, they must continue advancing high-quality methods for emerging and persistent contaminants. Water safety is no longer limited to a short list of classical pollutants. New chemicals, complex mixtures, and low-dose chronic exposures require increasingly sophisticated analytical tools. Second, they must democratize measurement. This means developing affordable, low-maintenance, low-power, field-ready systems that still meet meaningful standards of performance. It also means creating calibration protocols, reference materials, interlaboratory comparability, and transparent reporting frameworks so that results from different places can be trusted and acted upon.

In the end, chemical science does more than removing contaminants from water. It makes contamination visible. It turns uncertainty into evidence, and evidence into action. A doctor cannot heal responsibly without diagnosis. Likewise, no society can ensure sustainable access to clean water if it does not know, with confidence, what kind of water it actually has. Treatment matters. Infrastructure matters. Policy matters. But before the cure comes the test.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

***Accelerating universal clean water access:
bridging chemical sciences innovations
with mathematics and policy***

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Access to clean water is no longer a distant issue but a pressing challenge affecting communities worldwide. The Netflix documentary 'Brave Blue World' spans five continents, showing alarming footage of water shortages and contamination that urge humanity to rethink water management.¹ Despite these challenges, the film offers an optimistic vision of how innovation and technology can help build sustainable water systems. Water is an invaluable resource that flows through every aspect of life. When clean water access fails, it affects planetary health, human wellbeing, and sustainable development. This issue is intensified by population growth, urbanisation, and climate change.² Recognising this urgency, the United Nations' Sustainable Development Goal (UN SDG) 6 commits countries to ensuring universal access to clean water by 2030. Nevertheless, over 2.1 billion people still lack safely managed water.³ The UN has warned of 'water bankruptcy', which reflects that water use exceeds the supply that the hydrology and climate can provide, causing irreparable damage to water-related natural capital.⁴ Before water resources are fully depleted, science-based solutions are essential, as presented in **Figure 1**. While chemical sciences drive innovations, mathematics and strategic policy frameworks complement these efforts by translating them into practical solutions for universal water access.

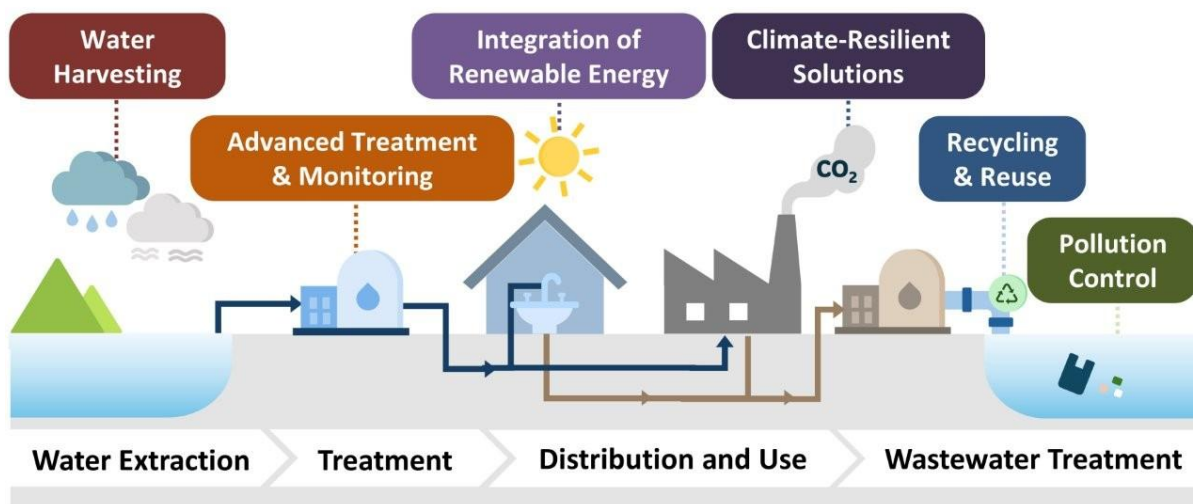


Figure 1 Water lifecycle from upstream to downstream involving water supply, treatment, use, and recycling, with key opportunities for improved clean water access

Chemical sciences are central to detecting, monitoring, and treating water contaminants. Conventional water treatment methods, such as filtration, coagulation, flocculation, and disinfection, rely on the chemical sciences principles.⁵ However, emerging contaminants often evade these treatment processes due to their persistence and bioaccumulative nature.⁶ Hence, research in this field has developed highly sensitive and precise analytical techniques for early detection of pollutants, enabling timely intervention to prevent escalating contamination. For example, Raman spectroscopy is widely used for the identification of microplastics,⁷ whereas liquid chromatography-mass spectrometry can effectively detect pharmaceuticals, polyfluoroalkyl substances, and personal care products.⁶ Beyond monitoring, chemical sciences devise targeted water treatment solutions to ensure a clean water supply to end users. For instance, advanced nanomaterials with high reactivity and large surface areas have been explored to enhance pollutant removal efficiency through adsorption, membrane filtration, and catalysis.⁸ Other than centralised water systems, point-of-use systems installed at specific

locations where water is consumed, such as chlorine-based tablets, solar water disinfection, and ceramic water filters, are also developed.⁹ These technologies are affordable and can be used effectively for safe drinking water production at the household level and in disaster settings. Additionally, chemical sciences design processes to harness alternative water resources, including desalination,¹⁰ fog capturing,¹¹ and rainwater harvesting,¹¹ to meet growing demand.

Today, climate change poses substantial threats to achieving universal clean water access by affecting not only water quantity but also quality.¹² The Intergovernmental Panel on Climate Change (IPCC) has highlighted that limiting global warming to below 1.5°C could halve the proportion of the global population experiencing climate change-induced water stress compared to 2°C.¹³ Extreme climatic conditions, such as droughts and floods, exacerbate water contamination by promoting bacterial growth and increasing pollutant levels,¹⁴ while saltwater intrusion and acidification alter water chemistry. To tackle this issue, chemical sciences provide climate-resilient solutions. Advanced materials, such as biosorbents and catalysts derived from marine,¹⁵ forestry,¹⁵ agricultural,¹⁶ and food wastes,¹⁶ can improve contaminant removal while reducing carbon footprints. Experimental research has also explored adsorption-based direct air capture of carbon dioxide using solar energy, in which adsorbents can be regenerated through *in situ* vapour-promoted desorption to capture carbon dioxide for industrial use while simultaneously recovering water. In addition to reducing energy consumption and greenhouse gas emissions, this approach also produces freshwater.¹⁷ By leveraging chemical sciences, these approaches address climate change and contribute to water systems with minimal environmental impact.

Despite advances in technologies driven by chemical sciences, mathematics is the key enabler in the efforts towards universal clean water access, as illustrated in **Figure 2**. Mathematical modelling and simulation underpin experimental research by providing data-driven insights for technology development. Notably, reaction kinetics models are commonly used to predict and analyse the biodegradation and adsorption rates of pollutants.^{18,19} This provides a better understanding of the mechanisms that aid in scaling up treatment technologies and optimising operating conditions. In early development, mathematical tools such as computer-aided molecular design can be applied to screen and identify potential candidates for experimental testing, such as selecting polymeric structures for membranes and compatible solvents,²⁰ to reduce reliance on costly trial-and-error experiments.²¹ Importantly, modelling links chemistry with economic and sustainability considerations through multi-objective optimisation. A previous study employed mathematical optimisation for nanofiltration regeneration network design and membrane selection to minimise cost and water usage.²² This approach has also been explored for sustainable water network design in the steel industry, considering alternative routes for water reuse in single-plant and multi-plant scenarios.²³ These findings can aid the decision-makers in infrastructure planning for ensuring clean water access. With various innovations enabled by chemical sciences, the application of life cycle assessment (LCA) to quantify their environmental impact across the entire life cycle from production of raw materials to disposal is essential. LCA studies often explore the impact of alternative membrane materials to replace polymeric materials in water treatment, which are major contributors to secondary pollution during disposal.²⁴ Hence, chemical sciences, coupled with mathematics, can transform technologies from laboratory innovations to practical, real-world applications to improve clean water access.

Indeed, chemical sciences can be complemented by mathematical modelling to support the transition towards climate-resilient water systems worldwide. This transition requires strong synergies between the water and energy sectors due to their close interconnection. The energy sector accounts for approximately 10% of total freshwater withdrawal,²⁵ whereas the water sector consumes roughly 4% of global electricity.²⁶ Thus, a holistic approach is to establish a water-energy (WE) nexus, where water and energy are managed as interconnected resource loops. In such systems, the outputs of one process can serve as the inputs to another. For example, treated wastewater can be reused as an alternative water source for the energy sector, reducing reliance on energy-intensive desalination while lowering both freshwater and energy demand. A recent study proposed a framework for urban-scale water and energy planning to optimise resource allocation and emissions reduction under policy constraints outlined in the Water Resources Plan.²⁷ By integrating wastewater regeneration, up to 95% of water demand could be met while reducing energy consumption by 28% and emissions by 34%. This strategy can be extended beyond WE security to include other sectors, such as the water-energy-food (WEF) nexus promoted by the UN. Supported by mathematical modelling, chemical sciences help mitigate climate change risks through water storage and reuse, energy recovery, and nutrient recovery.²⁸ Such integrated approaches ensure that limited freshwater resources are prioritised for essential uses, such as potable water and sanitation. By treating water and other resources as interconnected loops rather than isolated processes, more efficient and sustainable solutions can be achieved to improve water accessibility.

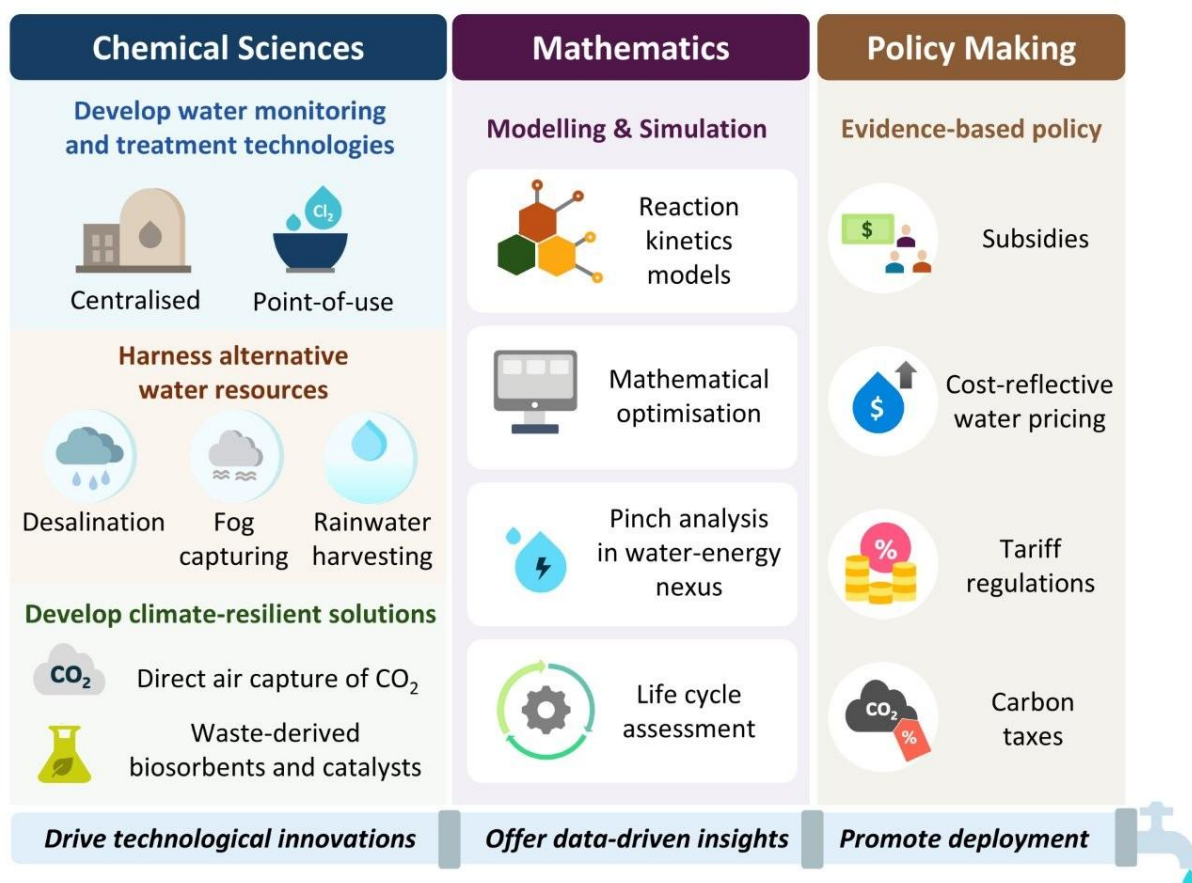


Figure 2 A collaborative nexus of chemical sciences, mathematics, and policy is essential for improving universal access to clean water

However, not all water management strategies are accessible to every individual. It is estimated that only 81% of the global population will have access to safely managed water by 2030, requiring a quadrupled progress rate to improve accessibility.²⁹ Inequalities exist across regions, countries, urban and rural areas, and vulnerable communities.¹² As discussed in ‘Poor Economics’ by Nobel laureates Banerjee and Duflo, communities facing poverty may prioritise items such as television or radio over improved water sources, even when financial support is available.³⁰ This reveals a critical insight that while chemical sciences and mathematical modelling have enabled technologies to address water-related issues, achieving universal access to clean water depends on policies that motivate their adoption. Thus, collaboration between policymakers, chemical sciences, and mathematical modelling is essential, as shown in **Figure 2**. Global policy frameworks, such as Integrated Water Resources Management, promote cross-sectoral strategies to maximise socio-economic benefits.³¹ In India, for instance, where the agricultural sector dominates water use, intensive irrigation and pollution have contributed to groundwater depletion.³² This highlights the need for policies that incentivise sustainable practices. Although chemical sciences and mathematical modelling support evidence-based policy formulation, targeted incentives, such as subsidies,³² cost-reflective water pricing,³³ and education, are crucial to encourage the adoption of water-efficient technologies and conservation behaviours. These strategies improve the financial sustainability of water services while maintaining affordable access to clean water.³³ Furthermore, modern wastewater treatment systems have evolved from linear, end-of-pipe designs into circular systems that prioritise reducing, preserving, and optimising water usage.³⁴ Tariff regulations can promote investment in water-efficient technologies to support the circular water economy.³⁵ Recent research has also introduced a predictive model to examine the indirect effects of carbon taxes on water footprints, providing insights to guide policy decisions.³⁶ These examples demonstrate the importance of aligning policies with technological innovation to ensure equitable water solutions.

While chemical sciences drive technology development, mathematical insights are essential for translating these innovations into practical solutions, and strategic policy frameworks ensure their adoption. We no longer need to simply ‘rethink’ water management as suggested in ‘Brave Blue World’, we now have the right tools to

“redesign” it. By harnessing chemical sciences innovations through mathematics and policy, humanity can turn the documentary’s optimistic vision into reality to build a sustainable, technology-driven water future for all.

Statement on use of AI

AI was not used. Grammarly was used in the preparation of this essay for the purpose of checking the grammar. The figures are constructed using Microsoft PowerPoint.

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Finalist

Action-enabling chemical design for equitable water access

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Introduction

We have sent rovers to search for water on Mars. Yet on Earth, one in four people cannot reliably access safe drinking water at home¹. The problem was never discovery, it was design. Access to clean water is often framed as a technological challenge. Over recent decades, the chemical sciences have delivered increasingly sophisticated solutions, including advanced membranes with improved fouling resistance, catalytic oxidation systems for persistent pollutants, and highly sensitive analytical tools capable of detecting contaminants at trace levels²⁻⁵. Despite these advances, water insecurity persists across diverse regions of the world, affecting both communities lacking infrastructure and those exposed to contaminated water sources^{6,7}.

In many large and rapidly industrializing systems, advanced treatment facilities may coexist with regions that rely on untreated groundwater or surface water. At the same time, expanding industrial activity and informal wastewater discharge contribute to complex contamination burdens in shared water sources^{8,9}. Addressing this gap requires a shift in perspective. Rather than focusing solely on performance under controlled conditions, chemical innovation must also enable effective intervention in real-world contexts. This is the principle of action-enabling chemical design.

Structural pathways of water insecurity

Water insecurity does not arise from a single structural failure, but from multiple overlapping pathways. In some contexts, infrastructure disparity remains the dominant constraint. Geographically expansive or decentralized systems often exhibit uneven distribution of treatment facilities, where urban centres benefit from advanced infrastructure while rural or peri-urban communities rely on untreated groundwater or surface water¹⁰. Maintenance fragility, limited technical capacity, and supply chain constraints can further undermine the reliability of centralized systems.

In other contexts, water insecurity is driven more by pollution pressure than by lack of infrastructure. River systems in parts of South and Southeast Asia, Sub-Saharan Africa, Latin America, and even industrial regions within high-income countries illustrate how industrial discharge, small-scale manufacturing, and informal settlements can contribute to complex contamination burdens¹¹⁻¹³. Although environmental standards may exist, variability in monitoring capacity, enforcement, and cost of compliance for small operators can allow pollutants to persist in shared water sources.

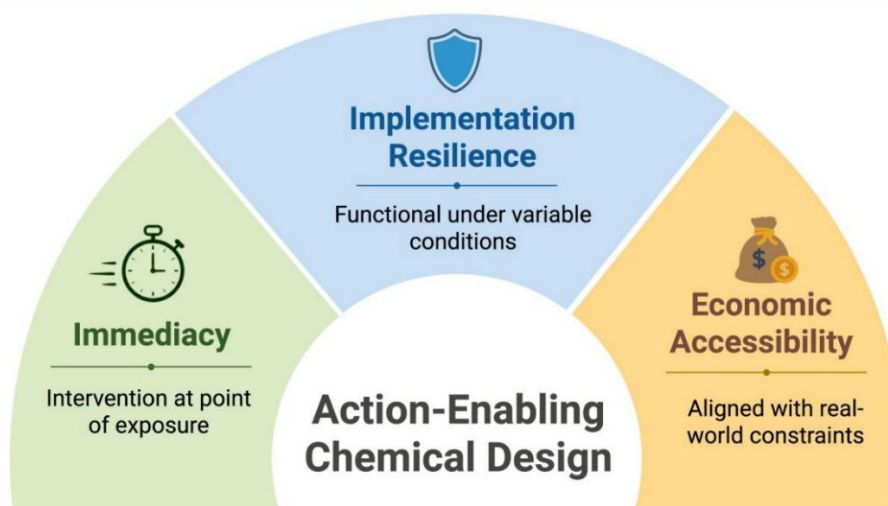
High-performance treatment technologies are often available, but their effectiveness relies on stable maintenance, technical expertise, and financial continuity^{14,15}. Water insecurity thus stems not only from technological limitations, but also from a misalignment between how technologies are designed and how they are actually implemented.

Defining action-enabling chemical design

Action-enabling chemical design is about developing chemical systems that actually translate scientific capability into reliable intervention under real, often variable conditions. This shifts the central question from “How well does this work?” to “Where, when, and for whom does this actually work?”. The defining characteristic is not only technical effectiveness, but whether it can be deployed. Such systems are designed to function across diverse economic, infrastructural, and institutional contexts, rather than under idealized conditions alone.

This approach represents a shift in design orientation. Traditional innovation often prioritizes performance metrics such as removal efficiency, reaction rates, or detection sensitivity. While these remain important, they do not guarantee sustained effectiveness in practice. Action-enabling design expands the scope of evaluation to include how technologies are deployed, maintained, and adopted.

Three principles characterize this approach. The first is immediacy, which emphasizes enabling intervention at the point of exposure or discharge. The second is implementation resilience, referring to the capacity of technologies to remain functional despite variability in maintenance, energy availability, or technical expertise. The third is economic accessibility, which ensures that the cost of protection is within reach of users and operators. Together, these principles shift chemical design from performance optimization toward enabling sustained protection in real-world settings, as illustrated in **Figure 1**. This shift in design orientation—from performance-driven development to implementation-informed criteria—is further illustrated in **Figure 2**.



Enabling equitable water access

Figure 1 Conceptual framework of action-enabling chemical design for equitable water access, organized around three complementary principles: immediacy, implementation resilience, and economic accessibility.

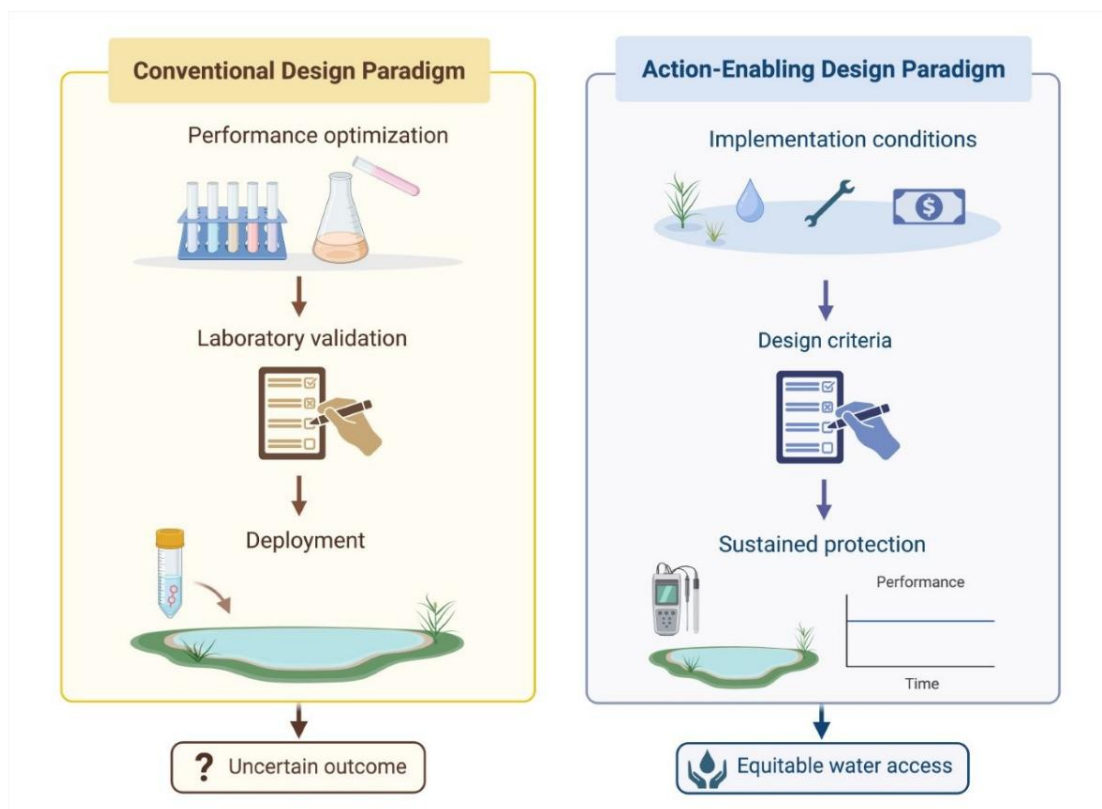


Figure 2 Comparison of conventional performance-oriented design and action-enabling chemical design, illustrating a shift from laboratory-centred development toward implementation-informed criteria that support sustained protection and equitable water access.

Operationalizing action-enabling chemical design

The principle of immediacy focuses on reducing the distance between contamination and intervention. In many contexts where centralized infrastructure is limited or unevenly distributed, decentralized treatment approaches can provide more immediate protection¹⁶.

Iron-based adsorption systems, including zero-valent iron and iron oxyhydroxides, have been widely applied for decentralized arsenic removal in groundwater. These systems demonstrate how relatively simple surface chemistry can deliver effective treatment without reliance on complex infrastructure^{17,18}.

Membrane technologies can also be adapted to support immediacy. Gravity-driven ultrafiltration systems, which operate without high-pressure pumps, have been implemented in parts of Southeast Asia, including Java, demonstrating that effective pathogen removal can be achieved under low-energy conditions^{19,20}. In parallel, portable and point-of-care sensing can complement these systems. Simple detection tools can identify contamination at the point of use^{21,22}, but their value lies in enabling immediate response when paired with accessible mitigation or treatment pathways. Advances in responsive materials now enable real-time, in-situ water quality monitoring — for example, self-healing dielectric sensors have demonstrated millisecond-response contamination detection without centralized laboratory infrastructure, enabling timely corrective action at the point of use²³. By shortening the interval between contamination and intervention, such approaches support more responsive and distributed water protection.

While immediacy addresses where intervention occurs, implementation resilience addresses whether it can be sustained. Many technologies perform well under controlled conditions but depend on consistent maintenance, reliable supply chains, and skilled operation. In practice, these conditions often vary.

Designing for implementation resilience requires reducing system fragility. Passive treatment systems, such as slow sand filtration or reactive barriers, illustrate how effective treatment can be achieved with minimal operational input^{24,25}. Similarly, chemical systems that reduce dependence on continuous reagent supply or precise dosing are more likely to remain functional in resource-constrained settings.

Material durability also plays an important role. Fouling-resistant membranes, long-lasting adsorbents, and catalytic systems with sustained activity can reduce maintenance frequency and operational complexity^{26,27}. In some cases, self-indicating materials that signal saturation or performance decline can enhance reliability by enabling timely intervention without sophisticated monitoring²⁸. These approaches prioritize consistent functionality over peak performance, so that technologies remain effective under variable conditions.

Economic accessibility forms the third pillar of action-enabling chemical design. Even when technologies are technically effective, their adoption is often constrained by cost. High capital investment, recurring operational expenses, and dependence on specialized materials can limit uptake^{6,7}.

Upstream innovation can help address these challenges. Cleaner dye chemistries, reduced-salt textile processes, and more biodegradable intermediates can reduce pollutant generation at the source, lowering downstream treatment demands^{29–32}. For industrial applications, modular catalytic pre-treatment systems or reusable heterogeneous catalysts can reduce the cost of wastewater treatment, making compliance more feasible for small and medium-scale enterprises^{27,33,34}.

Economic accessibility also includes resource recovery. Processes such as nutrient recovery through struvite precipitation, conversion of sludge into functional adsorbents, and recovery of valuable metals from waste streams can transform waste management into a source of value^{35–40}. By aligning chemical design with economic realities, these approaches make environmental protection more attainable and scalable.

Bridging innovation and implementation

Without alignment between chemical innovation and institutional systems, even the most advanced technologies remain functionally irrelevant. Their impact depends on alignment with regulatory frameworks, financing structures, and local production capacities. Action-enabling technologies do not replace environmental governance, but they can reduce the operational burden placed upon it.

Regulatory frameworks can actively incentivize this shift. Research on water reuse adoption has demonstrated that institutional coordination and well-structured policy instruments are among the strongest enablers of water technology uptake, while fragmented or contradicting regulations consistently act as barriers — even when technically effective solutions are available⁴¹. This suggests that procurement standards and financing mechanisms favouring locally maintainable, context-appropriate technologies could create meaningful market pull for action-enabling designs.

Conclusions

Sustainable access to clean water will not be achieved through technological advancement alone. The persistence of water insecurity reflects a misalignment between performance-oriented innovation and real-world implementation conditions. Action-enabling chemical design offers a constructive pathway forward.

Beyond technical innovation, realizing action-enabling chemical design at scale requires structural shifts in how research is prioritized and evaluated. Funding mechanisms that reward deployability alongside performance, along with training programs that expose chemists to implementation realities, would accelerate this transition. Journal publishers and institutions which increasingly recognize "real-world readiness" as a research outcome would further embed these values. The future of clean water will not be determined by how advanced our chemistry becomes, but by how effectively it is translated into protection where it is most needed. Chemistry does not fail when it lacks sophistication, it fails when it cannot act.

Statement on use of AI

Use of Artificial Intelligence (AI): AI was used in the preparation of this essay solely for grammar and language refinement (Grammarly and Claude). All scientific ideas, content, figures, and conclusions were developed independently by the author, who takes full responsibility for the final manuscript.

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Finalist

Light-to-heat: photothermal desalination for water scarcity

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Water covers roughly three-quarters of the Earth's surface, yet only a tiny fraction (less than 1%) is suitable for drinking and sanitation, with the rest being in the ocean or frozen.¹ As population and industrial activities grow, the gap between reliable supply and demand continues to widen. As shown in **Figure 1a**, recent global estimates indicate that more than two billion people still lack clean drinking water, and about 3.4 billion lack safely managed sanitation.² Health consequences, such as diarrhoeal diseases and intestinal infections from waterborne bacteria and viruses are prevalent in areas of high water stress.³ Consequently, pressure from industrial and domestic growth may drive global water demand by ~20–30% by 2050.⁴ In many regions, with the over-extraction of surface water and groundwater reserves beyond safe limits, the world has come to a state of "water bankruptcy",^{5,6} a condition where withdrawals exceed replenishment. Climate change, urbanisation and overall environmental degradation further destabilise supply by intensifying droughts and making precipitation patterns more erratic.⁷ Together, these pressures make water scarcity one of the defining global challenges of the 21st century, influencing global economy, geopolitics and public health. The world must therefore pursue solutions beyond infrastructure expansion to address energy, material and real-world deployment constraints. In this setting, chemical sciences can be a game-changer for achieving water security through desalination technology. Desalination, which is defined as the removal of salt from saline water, unlocks the ocean as a vast resource of freshwater while reducing pressure from natural freshwater ecosystems.⁸ Recent estimates place global desalination capacity at roughly 110–115 billion L day⁻¹, deployed across 177 countries.⁹

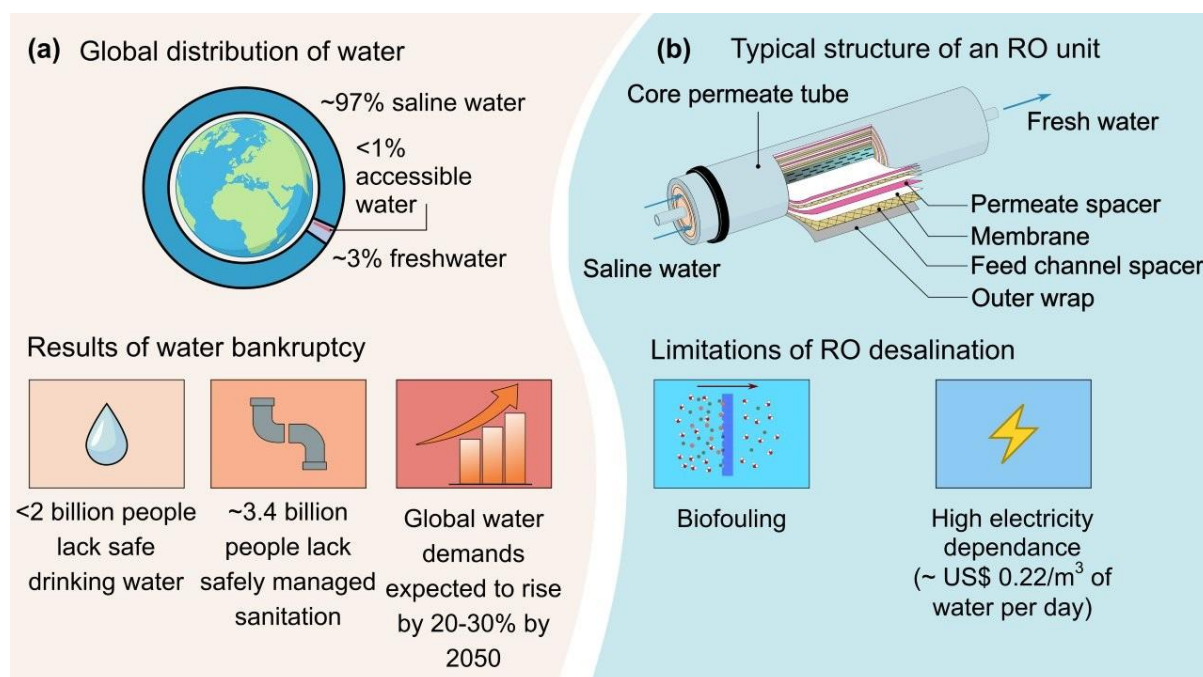


Figure 1 Infographic about water scarcity and conventional SWRO desalination. (a) Results of water bankruptcy. (b) Structure of an SWRO unit (top) and limitations of SWRO desalination (bottom).

The most commonly used desalination technology is reverse osmosis (RO), which follows the principle of pressure-driven ion separation by passing saline water through a semi-permeable barrier (membrane). Shown in **Figure 1b**, a general RO unit consists of a spacer to let feed water through, a membrane and a permeate layer to collect the desalinated water. RO membranes are thin-film composite (TFC) systems in which an ultrathin

polyamide selective layer governs water transport with a porous support. A typical TFC-based seawater reverse osmosis (SWRO) system can deliver clean water flux of about $12\text{--}17\text{ L m}^{-2}\text{ h}^{-1}$ and can cost around US\$ 0.5–2 per m^3 of water.¹⁰ However, while SWRO systems boast a high water flux and salt rejection, high-purity water production can require additional passes or post-treatments, and RO can be less effective against removing neutral species (e.g., boron) and microplastics.¹¹ Also, TFC performance depends on surface charge, free volume, and morphology,¹² all of which can be disrupted by biofouling (blocking of membrane pores) shortening membrane life, and raising the required operating pressure, increasing energy costs.¹³ While next-generation membranes (biomimetic channels,¹⁴ carbon nanomaterials,^{15,16} metal-organic hybrids¹⁷) are actively explored, many still suffer from scalability and long-term stability issues. To summarize, RO is a mature and indispensable technology, but improving affordability and resilience hangs on chemistry-driven solutions such as anti-fouling surfaces, longer-life materials, and lower-energy operation rather than engineering alone. One example to offset this energy demand is to use solar cells to generate the electricity necessary to operate them, however, solar-powered RO often needs storage or grid backup and large area to maintain reliable output. Moreover, sub-standard environmental conditions such as on a large oil tanker, or in a remote village without routine maintenance, can quickly exacerbate the performance of solar cells and membranes alike.¹⁸ Thus, RO's remaining bottlenecks are not merely engineering challenges, but deeper material and interfacial constraints. Therefore, ensuring sustainable access to clean water remains, to a large extent, a problem that must be addressed through innovations in the chemical sciences.

An alternative technology is thermal desalination (**Figure 2a**), where heat is supplied to seawater to drive evaporation and the resulting vapour is condensed to yield freshwater. The most established thermal desalination technologies are multistage flash distillation (MSF) and multi-effect distillation (MED). These processes are industrially mature, but they are typically energy intensive and have a higher initial capital cost (about double of an SWRO plant),¹⁰ which is a key reason why SWRO has become the dominant technology for desalination in many regions.¹⁹

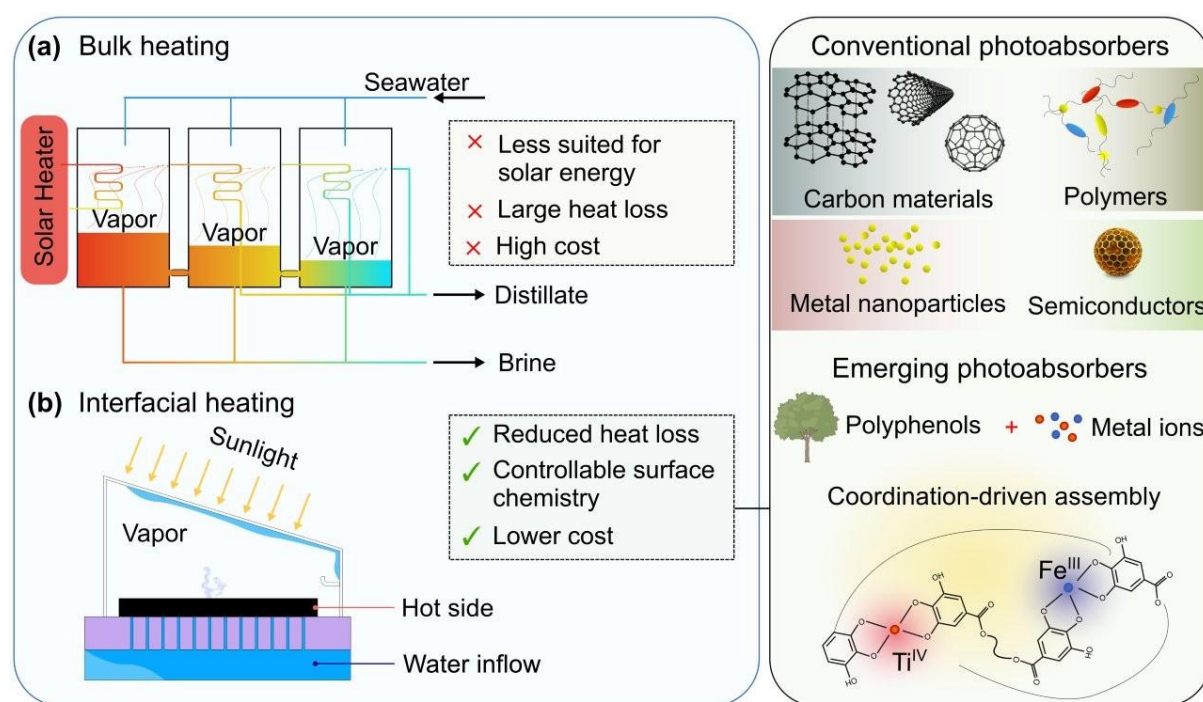


Figure 2 Chemistry-enabled transition of solar-thermal distillation technology. **(a)** Bulk heating architectures such as MED (shown). **(b)** Advantages of STDT with conventional and emerging photoabsorbers (right)

Advances in the chemical sciences, however, can help revive thermal desalination in a new form, by shifting the heat source from grid electricity to direct solar-thermal conversion (**Figure 2b**). Solar-thermal distillation (STDT) uses a photothermal material to convert sunlight into localized heat to accelerate evaporation of seawater, where the vapour is condensed as clean water. The performance of STDT depends on photothermal material design, including molecular and electronic structure, non-radiative energy relaxation pathway, and interfacial chemistry.^{19,20} By tailoring these properties of photothermal materials, chemists and chemical engineers can even reduce water evaporation enthalpy.²¹ At the device level, STDT can be classified into two

heating architectures: (i) bottom surface heating and (ii) interfacial heating. Among them, interfacial heating has gained the most attention because it localises heat at the air-water interface, and for its ease in tuning photothermal material parameters, while reducing bulk energy and material loss, enabling efficient operation even at low temperatures.²²

A key sustainability question, though, is whether photothermal materials themselves can be made abundant, safe, and scalable. For example, although solar absorbers like metal nanoparticles (Au, Ag etc.) and carbon nanomaterials (graphene,²³ carbon nanotubes,²⁴ and carbon black²⁵) have shown a high photothermal conversion efficiency, their broader deployment beyond laboratory scale is limited due to high costs, narrow-band solar absorption, performance degradation and scalability.²⁶ This assessment is, however, changing due to recent advancements in chemical sciences. A very recent example is the use of a polyphenol-based, metal-crosslinked ink that can convert more than 95% of the absorbed light into heat.²⁷ Polyphenols containing catechol/gallol groups (e.g., tannic acid) are cheap plant-derived compounds, commonly found in everyday foods such as tea, wine and chocolates, that possess diverse physicochemical properties including antioxidation, metal coordination and light absorbance.²⁸ By coordinating polyphenols with different transition metal ions, this light absorbance can be extended from the UV to visible and infrared (IR) regions.²⁹ When incorporated as solar-absorbing interfaces for steam generation, these nature-derived materials exceed most solar steam generators in terms of cost, performance and sustainability.³⁰

Overall, STDT can be designed to operate without high-pressure pumps and can practically eliminate the need for grid electricity as the heating source is the sun. To briefly compare, the dominant cost for thermal and SWRO plants is energy. On average, energy consists of two-thirds of total running cost for a typical MED thermal plant (US\$0.37/m³) and about half of total running cost for an SWRO plant (US\$0.22/m³). If we assume that 100,000 m³ of water is produced per day, a projected annual cost saving of about US\$13.5 million for thermal and US\$8 million for SWRO can be realized.¹⁰ Connecting this directly to the current price of electricity (US\$0.164/kWh),³¹ we can achieve an electrical energy saving of 82.3 GWh for thermal and 49.0 GWh for SWRO.

Despite being a highly sustainable and resilient solution to ensure fresh water for all, STDT technology has not reached the level of maturity that membrane desalination has achieved and there are several challenges to overcome. STDT units are weather-dependent and require substantial area for providing adequate amount of water at the municipal level. Moreover, due to its relatively low-water output compared to commercial RO filtration units, capital investments are scarce for large-scale material and device development. These limitations mean solar-thermal systems are currently viewed as a complement to RO and water recycling, rather than a replacement for municipal-scale water production systems. Significant investment approaches are being explored, such as the ongoing XPRIZE Water Scarcity by the Mohamed bin Zayed Water Initiative (<https://www.xprize.org/competitions/water>), in collaboration with governments and entrepreneurs, which encourages private sector companies and universities to invest more in developing emerging desalination technologies at scale. As the current global outlook shifts towards greener and more sustainable technology, chemical sciences will not only keep overcoming the challenges faced by STDT technology to provide a route for clean water access with minimal electricity and maintenance, it will also concurrently improve the performance of RO membranes through better antifouling chemistry, and longer lifetimes that reduce cost and waste.

In confronting global water scarcity, chemical sciences must balance innovation with responsibility: we must not only pursue peak efficiency under laboratory conditions, but design materials and systems that remain robust, affordable, and environmentally compatible. Meeting SDG 6 (Clean Water) is a multi-faceted goal that is supported by SDG 7 (Clean Energy), 12 (Responsible Production), and 13 (Climate Action). If desalination is to expand, its sustainability will depend on simultaneous progress in energy decarbonisation, material development, and accessibility. By strengthening RO and accelerating solar-thermal desalination performance through photothermal materials, the chemical sciences can help shift water security from a single tech-heavy model toward a hybrid, decentralised one that is more equitable, resilient, and aligned with global sustainability goals

Statement on use of AI

ChatGPT was used in the preparation of this essay for the enhancement of its grammar, flow and diction. The author thoroughly revised the essay and takes full responsibility for the content.

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Finalist

Arsiron Nilogon and Fluoride Nilogon: sustainable technologies for clean drinking water

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Introduction

This essay narrates an effort of a research group for sustainable clean drinking water. Water is the foundation of life, yet access to clean drinking water remains a global challenge. One in three people globally lacks safe drinking water as enshrined in United Nations (UN) Sustainable Development Goal (SDG) 6: “*clean water and sanitation for all by 2030*”.¹ The main source of water- surface water, groundwater and wastewater face unique challenges of biological and chemical contaminations including emerging pollutants like microplastics and pharmaceutical residues.² Over 1.5 billion individuals rely primarily on groundwater for drinking given its relative protection from microbial hazards.³ However, presence of various natural, geogenic and chemical contaminants such as arsenic, fluoride and heavy metal ions in groundwater compromises the health of millions.^{4,5}

Arsenic and fluoride in groundwater poses serious health risks. Prolonged consumption of arsenic contaminated water causes various forms of arsenicosis, linked to cardiovascular disease, diabetes, negative impacts on cognitive development, increased deaths in young adults and is a potential carcinogen.^{6,7} World Health Organisation (WHO) estimates about 140 million people worldwide consume water with arsenic above its the provisional guideline value of 10µg/L with extreme exposure reported in different countries across continents.^{8,9} Fluoride, beneficial to human teeth and bones at 0.5-1.0mg/L, becomes harmful when exceeds WHO guideline of 1.5mg/L leading to irreversible skeletal or non-skeletal and dental fluorosis. An estimated 200 million individuals worldwide consume fluoride contaminated water particularly in Asia and Africa.⁸

Several techniques like ion exchange resins, activated alumina, coagulation-adsorption, electro-coagulation, reverse osmosis, nanofiltration are developed, tested and employed to tackle groundwater contamination that are low cost as well as sustainable.¹⁰⁻¹⁴ However, these are limited by high cost, power dependence, mineral loss, sludge generation, scalability, periodic replacement of adsorbent materials, tricky electrode maintenance and requirement for technical expertise making them unsuitable for rural contexts.¹⁵

Against this backdrop, this essay highlights two patented technologies developed by our research group - Arsiron Nilogon and Fluoride Nilogon. Designed for simplicity, affordability, and efficiency, these are suitable for rural domestic settings as do-it-yourself (DIY) filters, as well as scalable for larger community-based applications.^{16,17}

What is Arsiron Nilogon

Arsiron Nilogon (**arsenic + iron** removal, Nilogon means removal in Assamese), based on Oxidation-coagulation-adsorption at optimized pH, is used to remove arsenic, iron and heavy metals from drinking water in presence or absence of coexisting iron (**Figure 1**).¹⁸⁻²¹ The method involves sequential addition at appropriate dose of three safe common chemicals- cooking soda powder, 5% potassium permanganate and 25% ferric chloride to the water to be treated in a reactor (**Table 1**) which creates an environment that mimics arsenic-free aquifers. Water is mildly stirred for thorough mixing of chemicals. Coagulation, as reddish-brown particles, is visible within minutes. The water is then filtered by a sand-gravel filter after one to two hours of residence time.

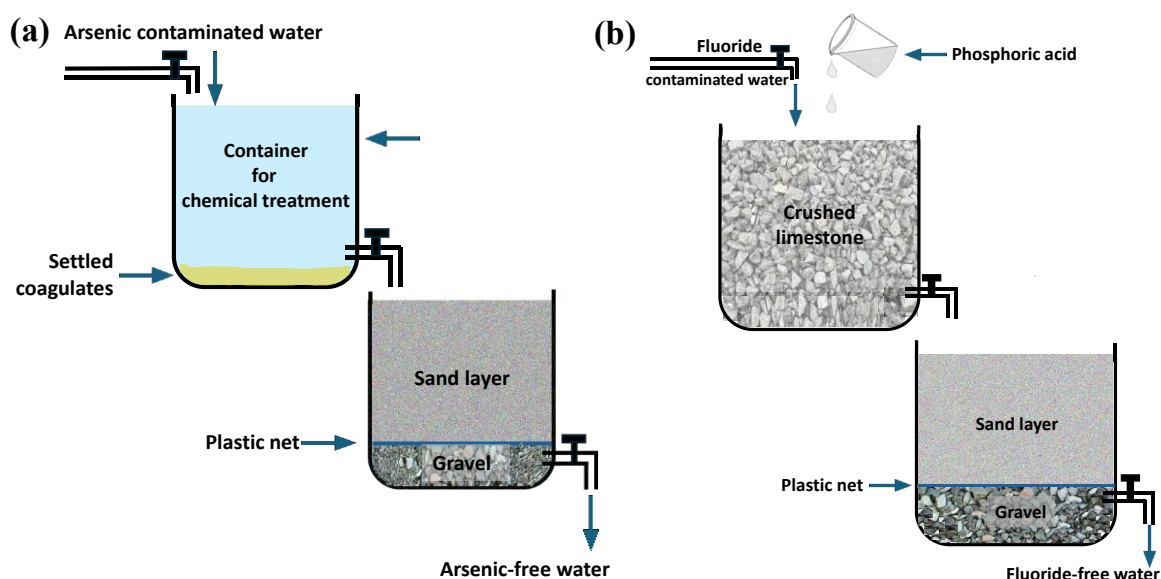


Figure 1 Schematic diagrams of (a) Arsiron Nilogon and (b) Fluoride Nilogon.

Table 1. The doses of the chemicals in Arsiron Nilogon in terms of weight per litre of water and their forms

Chemical	Dose	Form of the Chemical
Cooking soda	0.1 gL ⁻¹	White powder, or aq. solution
Potassium permanganate	0.5 mgL ⁻¹ *	5% (w/v) aq. solution
Ferric chloride	25 mgL ⁻¹	25% (w/v) aq. solution

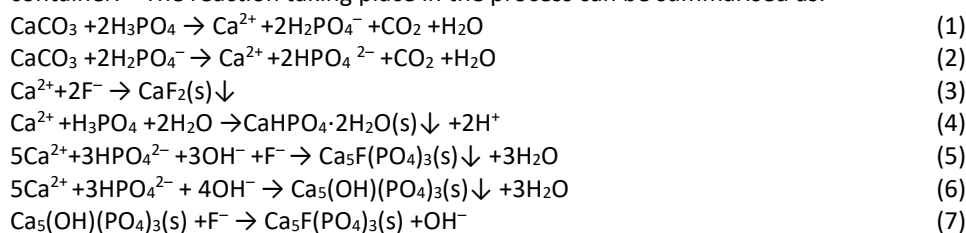
*More potassium permanganate should be added if the iron is also present in the water, until the colour of potassium permanganate continues to disappear

NaHCO₃ brings the pH initially to 8.3, ideal for arsenate adsorption and iron precipitation without affecting arsenate ion adsorption by competing OH⁻ ions. It ensures Mn⁷⁺ reduction to insoluble MnO₂, rather than soluble Mn²⁺ avoiding residual manganese in treated water. KMnO₄ oxidizes arsenite (As³⁺) to arsenate (As⁵⁺), which is easier to remove. MnO₂ also catalyse arsenite oxidation which otherwise has a half-life of months to years.²² KMnO₄ oxidizes Fe²⁺ to Fe³⁺ aiding coagulation. It also acts as a mild disinfectant, eliminating bacteria. FeCl₃ provides Fe³⁺ ions that coagulate as goethite and ferrihydrite to adsorb arsenate before being settled down. FeCl₃ hydrolysis lowers the pH from 8.3 to 7.3, middle of the safe range of 6.5–8.5 for drinking. Any preexisting iron can be utilized in Arsiron Nilogon, reducing the dose of FeCl₃.

For water with dissolved iron, the dissolved iron can be removed by simple sand-gravel filtration and then use Arsiron Nilogon as prescribed for iron free water. Alternatively, both can be removed together with a modified chemical dose.

What is Fluoride Nilogon

Phosphoric-acid-crushed limestone treatment (PACLT), or Fluoride Nilogon is a plug-flow method based on hybrid precipitation-adsorption where fluoride containing water pre-mixed with a very small quantity of phosphoric acid (**Table 2**) is treated in a 0.5-1.5 cm crushed-limestone bed reactor made of a plastic or an RRC container.²³ The reaction taking place in the process can be summarised as:²⁴



Within three hours of residence time, fluoride of any initial concentration drops to approximately 0.6 mg/L, aligning with the WHO's guideline for safe drinking water which is essential for normal tooth and bone.²⁴ Water is then allowed to pass through a sand-gravel filter (**Figure 1**). The dose of phosphoric acid to be added in water is fixed at 0.00068M. Alongside fluoride, the method is validated for efficient removal of heavy metals such as Hg, Cd, Ni, Cu, Cr, Mn, and Pb.²⁵

Table 2: Summary of filter types, unit counts and doses of PA in Fluoride Nilogon:

Filter type	Volume of reactor/L	Filtering capacity/L	Dose of PA/mL [#]
Household	40	15	7.0
Small community	200	80	37
Large community	5000	2200	100

#A small variation of the dose does not matter

Potability of treated water

The treated water from both methods meets potability standards. Both the methods do not leave any unwanted residues or foul odour to the water and leaves the total dissolved substances (TDS) intact.¹⁸ The pH of the treated water is about 7.5, middle of the acceptable pH range of drinking water, 6.5-8.5 as prescribed by BIS. Concentration of Fe, Mn, Na and Cl introduced in Arsiron Nilogon remain within WHO limits. Fluoride Nilogon slightly increases calcium concentration, which benefits fluoride-affected individuals, by reducing fluoride absorption in the body.²³

Cost-estimation

In addition to their technical efficiency, these methods are remarkably economical, with recurring chemical and capital expenses kept minimal. For both of Arsiron Nilogon and Fluoride Nilogon, the recurring cost of the chemicals in India is ~£0.05m⁻³ of treated water. The capital cost for a household Arsiron Nilogon and Fluoride Nilogon filter are ~£5 and ~£6, respectively.

Safe sludge management

Effective sludge management and disposal is critical for any sustainability chemical treatment technologies. Arsiron Nilogon produces only about 0.5g of solid sludge per 20 litres of treated water, which can be safely collected in simple earthen pots with a small hole at the bottom and half filled with sand and later disposed of in landfills or buried without risk of recontamination. It passes the US-EPA TCLP test, with arsenic leachate levels 500 times lower than US-EPA permissible limits of 5000µg/L for TCLP.²⁶ In Fluoride Nilogon, limestone bed can effectively function for at least the lifetime of the filter without replacement or regeneration and the minimal sludge generated shows fluoride leaching concentrations approximately 429 times lower than US-EPA's permissible limit of 150mg/L. which can even be repurposed for cement or rural road construction preventing any direct contact with the source water.²³

Reaching out to the society

Arsiron Nilogon filters have been in use in several arsenic affected states of India viz Assam, Bihar, Chhattisgarh, West Bengal and Uttar Pradesh (**Figure 2**).^{18,27,28} Two community scale 1000L filters were installed at Mrinaljyoti Rehabilitation Centre (MRC): home to about 400 children with physical and intellectual disabilities in Assam, India. The groundwater contained excess Mn, Pb, Hg, and Fe. The filters are now ensuring reliable access to clean drinking water for the children (**Figure 3**).²⁹ Similarly, Fluoride Nilogon has gained traction in the fluoride affected region of India including Assam, Rajasthan, Chhattisgarh, Odisha, Karnataka. Notably, 300 Fluoride Nilogon filters were installed in four villages in Lahj and Al Dhale'a governorates of the conflict affected Yemen by ZOA (**Figure 4**).^{24,30}



Figure 2 Arsiron Nilogon household filters in the Indian states of (a) Assam, (b) West Bengal, (c) Chhattisgarh, (d) Bihar, (e) Uttar Pradesh



Figure 3 Two 1000L small community filter which remove neurotoxic Mn, Hg and Pd along with Fe from drinking water to children with neurological issues at MRC in Assam



Figure 4 300 Fluoride Nilogon which includes (a,b) household and (b) community filters in four villages near Aden in Lahj Governorate in Yemen by ZOA

DIY filter & customisability- chemistry for every scale

A defining strength of these technologies is their scalability: from 40L household to 5000L large community units. **(Figure 5)**. The household units which include two plastic buckets, two plastic taps, sand and gravel embody a DIY spirit, enabling families to assemble themselves. Chemical doses can be adjusted depending on the volume of the water to be treated. This DIY nature reduces dependency on external agencies, fosters a sense of ownership among users and ensures these technologies are not one-size-fits-all but responsive to local realities.



Figure 5 A custom designed Arsiron Nilogon dosing unit at Jyotinagar Public Water Supply Scheme which worked for over 5 years in Golaghat, Assam, India.

Community engagement- the missing link in water security

Technical efficiency alone cannot ensure water security; social acceptance is the bridge to long-term sustainability. Our approach prioritizes community engagement and capacity building over external dependency. Through workshops and awareness programs, local volunteers formed within the users are trained to prepare and distribute chemicals, assist with filter installation and monitor performance **(Figure 6)**. To reinforce ownership, users are encouraged to construct simple filter stands themselves and maintain sand and gravel.



Figure 6 Community empowerment: (a,b) trained villagers making Fluoride Nilogon filters in Nuapada, Odisha, India (c) a user crushing limestone for his filter in Assam, and (d) an awareness cum training programme before distribution.

Conclusions

While centralized systems often struggle with maintenance and high operational costs, these technologies provide realistic model for use as stop-gap or as a standby arrangement during interruptions in the long run with minimum interventions requirement. Sustainable water security demands both technological innovation and social acceptance, supported by policy frameworks. To meet UN SDG 6, policy frameworks must integrate such validated methods into national water safety plans. Ultimately, these innovations demonstrate how chemical sciences can bridge scientific potential with universal access ensuring safe drinking water is not a privilege, but a guaranteed right for all.

Statement on use of AI

No artificial intelligence (AI) was used in the preparation of this essay.

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Finalist

The molecular shield: circular economy for water security in the Global South

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The liquid asset of Paraguay

In the heart of South America, the word "Paraguay" translates from Guaraní as "river that gives birth to the sea." With major rivers such as the Paraguay, Paraná, Apa and Pilcomayo defining its borders, and with the Guaraní Aquifer system below, one of the world's largest reservoirs of freshwater worldwide,¹ you could assume that water is the nation's most vital strategic asset. However, this abundance masks a fragile reality, and trouble comes from one of the most prolific industries in the country: agriculture.

Chemical sciences have long been used to maximize crop yields, but often at the expense of our water. In 2025, Paraguay's soybean production closed with an outstanding 10 million tons harvest, representing 81% of installed agricultural capacity across the sector.² Yet this success is linked to a traditional chemical approach: the application of fertilizers and pesticides. Unlike the nutrient-rich soils of neighbouring Argentina, Paraguay's land requires intensive nitrogen supplementation to sustain its soybean yields.³ Because of their low Cation Exchange Capacity (CEC), Paraguayan soils cannot hold onto ammonium (NH_4^+) as effectively as the clay-rich soils of Argentina so there is a need for fertilizers to be used in the country.⁴ While nitrogen is a fundamental building block for plant life, its high solubility in the form of nitrates (NO_3^-) poses a significant risk to aqueous environments.⁵ When nitrogen levels exceed the soil's capacity, these ions leach into groundwater through processes dictated by local hydrogeology, including topography and aquifer depth.⁶

When we spray our fields, we are not just feeding plants; we are inadvertently polluting our aquifers with nitrogen runoff and pesticide residues. As the most prevalent pollutant in aquifer systems, nitrate contamination is largely an anthropogenic byproduct of modern land use.⁷ To ensure sustainable access to clean water for all, the chemical sciences must achieve a molecular shield, severing the link between agricultural productivity and water contamination.

The science of prevention: beyond remediation

Sustainable water management has historically focused on remediation, cleaning the water once it is already dirty.^{8,9} In an increasingly industrialized global food system, nitrogen waste has become a systemic byproduct.¹⁰ However, the First Principle of Green Chemistry is Waste Prevention.¹¹ It is fundamentally more sustainable to prevent a pollutant from entering a watershed than to treat it at a municipal plant. Or, in this case, to treat the whole aquifer from nitrogen pollution.

The primary culprit in agricultural water contamination is "nutrient leaching." Nitrogen leaching is a highly discussed topic between academics to find a solution for this huge problem.¹²⁻¹⁴ When nitrogen-based fertilizers are applied, only up to 40-50% of the nitrogen is being incorporated into the agricultural products.¹⁵ Current chemical literature proposes several mitigation strategies ranging from nitrification and urease inhibitors,¹⁶ site specific nutrient management,¹⁷ deep placements of urea super granules,¹⁸ and ending with biological nitrogen fixation in some crops.¹⁹ Understanding the kinetics of nitrogen loss is a prerequisite for a 'Molecular Shield.' While strategies such as urease inhibitors and site-specific management provide incremental improvements, they do not address the fundamental design flaw of traditional fertilizers: their inherent lack of temporal control.

To protect this vital resource, we must move beyond site-specific management and deep placement of urea. We should embrace the 4th Principle of Green Chemistry 'Benign by Design' technologies,¹¹ such as bio-based nitrification inhibitors²⁰ and controlled-release matrices.²¹ More than being merely agricultural tools they are the chemical barriers that prevent the degradation of groundwater, ensuring that 'access to water' remains an affordable reality for the rural populations of the Global South, rather than a mounting technical and economic burden.

Biological nitrification inhibitors (BNIs) help reduce that nitrogen loss from agroecosystems previously characterized within these agroecosystems by inhibiting the specific soil microorganisms that convert stable ammonium into highly mobile nitrates.²⁰ This ensures that nitrogen remains available to the crop rather than being converted into mobile nitrates that threaten the integrity of freshwater systems like the Guaraní Aquifer. Simultaneously, polymer chemistry helps with a range of strategies to deal with issues like overfertilization and biodegradation by creating a tailored material design allowing controlled active components release.²¹ Polymers made from lignin, starch, cellulose or their modified forms are known to be part of this material design in biodegradable polymer-coated controlled-release fertilizers.²² While BNIs maintain nitrogen in the less mobile ammonium form, these bio-polymer coatings provide a physical barrier that synchronizes nutrient availability with the plant's biological clock.

Localized chemical interventions: the Paraguayan context

Current research focuses on *Nitrosomonas europaea* bioassays²⁰ but there is still a significant geographic lacuna in the application of this data to the Global South. Specifically, the highly acidic, low-CEC soils—which inherently struggle to adsorb ammonium cations (NH_4^+) but repels altogether the anion nitrate (NO_3^-), making the nitrate our primary leacher—of the Paraguayan Alto Paraná remain a 'terra incognita' for BNI efficacy.⁴ This presents a profound opportunity for bioprospecting within Paraguayan flora. The diverse secondary metabolites found in Paraguayan species as antioxidants, antifungal, and others could offer a natural, localized 'chemical arsenal' to protect our groundwater.^{23,24}

In a truly sustainable Paraguayan model, the controlled-release matrices would be derived from the lignocellulosic waste of the national sugarcane through an extraction from the bagasse.^{25–27} By extracting lignin from bagasse, we can create a 'closed loop' chemical system. When cross-linked with starch derived from mandioca (cassava),^{28,29} another staple of Paraguayan agriculture, we can work in a controlled-release profile. We can see this matrix in **Figure 1**, where lignin serves as a dual-functional hydrophobic barrier: it physically restricts water penetration while simultaneously inhibiting soil enzymes like α -amylase and starch hydrophilic nature allows water to penetrate this coat and work as a controlled-release fertilizer.³⁰ This prevents the 'burst release' of nitrates into the aquifer during the intense tropical rainfall's characteristic of Paraguay, ensuring that agricultural nutrients remain in the root zone rather than migrating into the Guaraní reservoir.



Figure 1 Part of the molecular shield: schematic representation of the bio-polymer composite matrix

Therefore, the synergistic application of BNIs to keep nitrogen in the ammonium form, combined with a starch-lignin matrix to physically slow its movement it's a chemical necessity to prevent the further nitrogen pollution of the Guaraní Aquifer.

Economic realism: bridging the "green premium"

The reality of a transition to a circular economy for water security requires more than molecular innovation as it also demands economic and systemic realism. In a developing economy like Paraguay, the primary barrier to sustainable chemistry is the "Green Premium", the higher market cost of controlled-release urea and BNI-enriched fertilizers compared to bulk urea.³¹ To ensure that clean water for all is not a luxury limited to the Global North, we must embrace circular economy inside our region.

This involves the strategic valorization of local agricultural side-streams already happening in Paraguay. When we work on controlled-release matrices from sugarcane bagasse or mandioca waste, we are ensuring a circular economy loop. Using waste from some industries to ensure a better yield in our agriculture and, at the same time, protecting our water from runoff, we are ensuring sustainable access to clean water for all needs. By transforming industrial waste into a "molecular shield" for the Guaraní Aquifer, we lower the cost of entry for local farmers in departments like Alto Paraná and Itapúa, aligning the immediate financial incentives of agriculture with the long-term necessity of water conservation.

Conclusions

The first Green Revolution of the 20th century successfully scaled global food production but left a legacy of nitrogen-saturated, vulnerable landscapes.³² The 21st century demands a Second Green Revolution, one powered by the chemical sciences but governed by the green chemistry principles of Waste Prevention and Benign by Design and circular economy prospects.

By dividing agricultural productivity from hydrological degradation using localized BNIs and bio-polymer matrices, we can safeguard the Guaraní Aquifer for the generations that follow, ensuring that clean water remains a fundamental right rather than a burgeoning technical luxury. As the translation of Paraguay suggests, the rivers that give birth to our seas deserves to be protected at their source. For a chemist like me, the most effective tool for water security is not an expensive filtration plant at the tap, but a smarter, more efficient molecule in the field.

Statement on use of AI

The generative AI tool Gemini was utilized exclusively for language editing, including grammar verification and improvements to the clarity and flow of the prose. The model was not used for scientific data analysis, the generation of original research content, or the creation of bibliographic references. All arguments, scientific interpretations, and conclusions presented in this essay remain the original intellectual property of the author.

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Finalist

Making “forever chemicals” not forever

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Per- and polyfluoroalkyl substances (PFAS), also known as the “forever chemicals,” are a group of synthetic chemicals widely used in industries in the 1940s, which are not biodegradable due to the strong carbon-fluorine bonds.¹ PFAS are detected in human blood and estimated to be present in 98% of the global population,¹ and are shown to have links with deadly cancer as well as liver damage,² threatening Sustainable Development Goals (SDG) 3 (Healthy life and well-being).³ Beyond that, PFAS threatens SDG 14 (Sustainable development of marine life) because they accumulate in marine animals and are passed on via food chains, which is dangerous because their toxicity can be magnified by 40% when combined with microplastics.⁴ In response to this crisis, the U.S. EPA limits the levels of PFOA and PFOS to 4.0 parts per trillion (ppt) and sets the MCLGs and MCLs of “GenX Chemicals” at 10 parts per trillion.² To meet these strict restrictions, several filtering methods are introduced: Granular Activated Carbon, which uses carbon to absorb chemicals as water passes through it, Ion Exchange Resins, which consist of tiny beads called resins that hold PFAS with electrostatic attraction to filter out from the water system, and reverse osmosis, which forces water through an extremely thin barrier and filters out PFAS.⁶

However, the true challenge is material stewardship, the responsibility for the environmental and social impacts of a material throughout its entire lifecycle.⁷ GenX Chemicals were once introduced as a substitute for PFOA (perfluorooctanoic acid). They were supposed to be less bioaccumulative and achieve material stewardship due to their shorter molecular length.⁸ However, Gen X is proven to be significantly more toxic than PFOAs, and is marked as the “regretful substitution”.⁹ To achieve SDG 6 (Clean water and sanitation) and SDG 12 (responsible production),³ we must shift our focus from “reallocating waste” to elimination methods like Advanced Oxidation Processes (AOPs). By generating 2.80V oxidation potential hydroxyl radicals electrochemically to break the high-energy carbon-fluorine bond, AOPs convert PFAS permanently into non-toxic inorganic constituents such as water, carbon dioxide, and calcium fluoride.¹⁰ This is essential to close the loop on PFAS pollution and ensure sustainable access to clean water for all needs.

PFAS is one of the most threatening forever chemicals because of its the C-F bonds. Fluorine is the most electronegative element, and C-F bonds are the strongest covalent bonds in organic chemistry.¹¹ The bond dissociation energy of the C-F bond, about 485 kJ/mol, is much higher than those of C-Cl (~327 kJ/mol) and C-Br (~285 kJ/mol).¹¹ AOP uses highly reactive species with high oxidation potentials that can cleave carbon-halogen bonds of pollutants in wastewaters. Oxidants are often radicals under aerobic condition, such as the hydroxyl radical ($\bullet\text{OH}$), superoxide radical anion ($\text{OO}\bullet^-$), and sulphate radical anion ($\text{SO}_4\bullet^-$). This essay focuses on the $\bullet\text{OH}$ radical, which has a 2.80V oxidation potential and standard thermodynamic potential of 2.73 at pH0.¹² This gives it enough thermodynamic driving force for PFAS oxidation.¹¹ Hydroxyl radicals are produced electrochemically by electrolysis, in which water is discharged on the BDD anode to produce hydroxyl radicals.¹³

Here is the actual process: to eliminate PFOA, an initial electron is transferred from the molecule to the anode, which is the rate-limiting step. PFOA is then decarboxylated, as the carboxylic group is attacked and loses a CO_2 group, to form perfluoroalkyl radicals ($\bullet\text{C}_n\text{F}_{2n+1}$). Then, the remaining molecule undergoes a cyclic “unzipping” mechanism by $\bullet\text{OH}$ radicals to form a shorter chain perfluoroalkyl by removing CF_2 and fully mineralise it into CO_2 and F^- . Finally, F^- can be safely mineralized as CaF_2 .¹¹ However, it will still be challenging because of the strong C-F bonds ($464.5 - 481.5 \text{ kJ mol}^{-1}$), so in order to bridge AOP to reality, we can start with the destruction of PFOS, as the bond dissociation energy of the C-S bond (272 kJ mol^{-1}) in PFOS is lower than that of C-C bonds and C-F bonds, allowing desulfonation,¹¹ which is more energy-favourable, to happen after the initial electron transfer.

AOP is considered a potential pathway to completely removing PFAS from water in the real world. Current technologies, such as adsorption and ion exchange, are primary separation techniques that only concentrate pollutants into a secondary waste stream as sludge or membranes,^{11,14} failing to eliminate PFAS completely. AOP, on the other hand, provides a superior alternative to traditional treatment methods because they aim for the complete mineralisation of PFAS into harmless species like CO_2 , H_2O , and F^- ions, which is later converted into CaF_2 . Furthermore, AOP aligns with SDG 6 as an environmentally friendly solution because of its efficient conversion of electrical energy into $\bullet\text{OH}$ radicals and its chemical-free operation.¹⁴ When powered by renewable

energies such as solar and wind energy, it can protect the environment by supporting SDG 7 (Affordable and clean energy) and SDG 12. It supports carbon-free production and won't contribute to global warming.

However, it will be challenging to jump out of the controlled "laboratory bubble" and truly carry out AOP on an industrial scale. A primary challenge is the presence of 'scavengers' in natural water sources, such as carbonate, bicarbonate, and natural organic matter (NOM). The •OH will also react with these additional substances in water bodies, and this significantly reduces the defluorination efficiency.¹⁴ This means that a huge amount of energy will be required to destroy PFAS completely in the water sample, making it economically unappealing. Another major bottleneck is the huge energy consumption of AOPs for PFAS removal.¹⁴ •OH radicals have a very short aqueous diffusion distance,¹¹ meaning that they won't be able to destroy PFAS unless the reaction occurs at the surface of the electrode. Consequently, a massive amount of energy will be needed to generate •OH radicals, which have a low probability of reacting with any PFAS before disappearing. Therefore, optimizing the energy-normalized removal capacity is crucial for making these technologies economically viable in the real world.¹¹

To tackle these challenges and achieve a sustainable future with clean water, instead of operating in larger and untreated water bodies, AOP should be included as part of a hybrid system. This can be achieved by combining traditional filtering methods and Electrochemical Oxidation (EO), which is currently considered a potential destruction scheme of PFAS by the EPA.¹⁵ After concentrating PFAS molecules through traditional filtering methods, the contaminated water can be passed into a localised cell, in which EO will occur directly at the surface of the BDD anode. By operating at ambient conditions,¹⁵ EO minimises the background molecules and maximises the efficiency of the process. It is a promising technology for PFAS destruction because of its lower energy demand to work compared to thermal incineration and avoidance of involvement with additional chemical oxidants.¹⁵

However, economic and mechanical problem remains. The high cost of BDD electrodes, being the most common electrode used with a cost of \$7,125/m², makes EO particularly expensive. Furthermore, the limited reacting space around the anode can lead to potential incomplete destruction of some PFAS in the water sample if they can't contact the surface. Despite this, research and results from tests are so far promising—a total removal of 77.2% of PFOA and 96.5% of PFOS is achieved with a Ti₄O₇ electrode, which cost about one-third of that of a BDD electrode.¹⁶ This makes EO much more achievable and successful, potentially able to be widely applied to industries in the future when Ti₄O₇ electrodes are commercialised.

To achieve a more sustainable world, green chemistry must play a leading role. We must shift our focus from merely transferring to eliminating forever chemicals before their environmental consequences become unstoppable. AOP is a very appealing solution; by "unzipping" PFAS molecules with •OH radicals, we can truly mineralise PFAS molecules into CaF₂ and CO₂. It will support SDG 3 and SDG 6 by protecting the population's health via the reduction of PFAS in water, as well as SDG 14 by reducing bioaccumulation of PFAS in marine life, thereby addressing its ongoing threats in the food chain. It also achieves material stewardship and supports SDG 12 (responsible production) by completing the life cycle of a PFAS molecule through mineralising it into other natural and safe substances with the cleanest reagent: electrons. While economical and mechanical challenges are faced in this journey, the combination of the promising EO technology with the use of sustainable energy in a hybrid system creates a more sustainable access to clean water, a fundamental requirement for quality of life for everyone.

Statement on use of AI

AI was used in the preparation of this essay to assist with formatting reference citations according to RSC guidelines and checking language clarity. The underlying scientific ideas, core research, selection of sources, and final synthesis remain entirely the original work of the author.

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Finalist

The chemical science perspective: approaches to acquiring sustainable access to clean water

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Introduction

In this essay three different perspectives on acquiring sustainable access to clean water, as followed, are discussed: (1) the alternative sustainable methods for water treatment, (2) the extensive testing of water using new techniques to make treatment more targeted and (3) tackling the root causes of poor water quality with reference to a circular economy approach. These three perspectives can all be linked to the chemical sciences in different ways. Water treatment is a vital part of our survival in modern day society as only 0.06% of fresh water is available to us.¹ Drinking water that is not clean leads to spread of many fatal diseases. A large part of water treatment requires the use of many chemicals, and over 700 different chemicals have been found in US drinking water, which makes a very big link between water treatment processes and the chemical sciences.¹

Perspective 1: alternative methods of water treatment

Many water treatment processes used to remove harmful pathogens and microbes can be damaging to the environment due to the use of heavy-duty chemicals or its contribution to climate change due to requiring high amounts of energy.² These methods can also be very expensive and so aren't accessible to lower income countries, making potable water inaccessible to anyone living there.² In this section of the essay greener, more environmentally friendly methods are discussed, that take advantage of the world's natural resources.

Advanced oxidation processes are environmentally friendly, chemical science methods of removing almost all types of pollutants from water by using oxidative degradation of contaminants.^{3,4,5} Reactive oxygen species (ROS) can be used in this process as they have extremely powerful oxidising capabilities, if able to be generated naturally, ROS could be a very sustainable water purification approach. ROS can be generated by activation of dissolved oxygen within water by natural reducing agents, the most common radical formed being a hydroxyl radical.^{4,6} However, there are some known downsides of using ROS including: excessive energy use and the formation of toxic byproducts particularly in halide containing water.⁶

Another advanced oxidation process includes photocatalysis.⁴ Photocatalysis is the enhancement of solar disinfection.⁴ When a photocatalyst is exposed to light at a sufficient wavelength/energy, the energy of the photons are absorbed by electrons, promoting them from a valence band, to a conduction band and in this process a hole in the valance band is formed (**Figure 1**).³ This generates a hole and electron pair, used to oxidise and reduce substrates respectively, creating an environment where substrates can be oxidised and reduced spontaneously.³ Photocatalysts are semiconductor materials, such as Fe_2O_3 , which even work at room temperature, reducing the energy requirement.³ The method of photocatalysis is considered a green chemical pathway, which is in line with reducing water treatment environmental impacts using chemical science.³

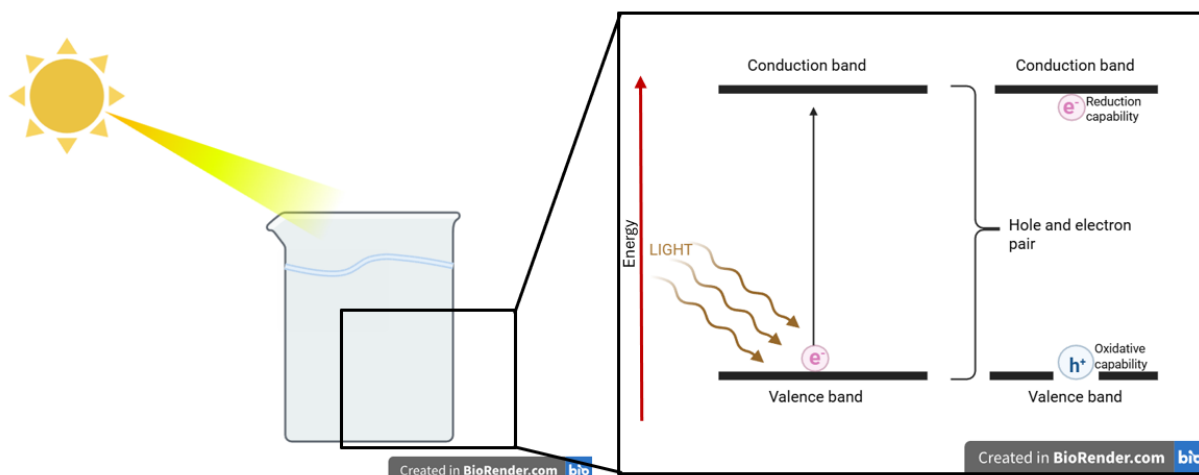


Figure 1 Shows the general principle of photocatalysis and how it creates an environment in which substrates can be oxidised and reduced through the hole (h^+) and electron (e^-) pair.^{3, 16}

Advanced oxidation processes can also be used in leachate treatment and ground water remediation, which links to the third perspective of tackling the root cause with a circular economy approach.⁴

Perspective 2: advantages of thorough water testing

The perspective of this section is based on the idea that if there was more frequent and thorough testing of water sources before treatment, the treatment could then be more targeted and use less chemicals, which ultimately would be more affordable and accessible to the world's population. Also focusing on how testing of water can be advantageous in many different ways. In order for potable water production to head towards sustainability, effective methods must be adopted which requires chemical analysis along with toxicity tests.⁷

Aquaphotomics is a new discipline that appeared in the early 2000s and is a very interesting way to test water and identify any molecules within water samples.⁸ Aquaphotomics uses near infrared spectroscopy to monitor the wavelength of different water samples, giving information on their water matrix coordinates that link to specific water structures and functions.⁹ This monitoring technique provides evidence that water changes in response to its environment and the other molecules present in it.⁹ Furthermore, this also helps in understanding the way water interacts with other compounds.^{8,9} For example, salts that don't even absorb near infrared light can be detected with high precision based on the changes they make in the water molecular system/network using Aquaphotomics.¹⁰ Aquaphotomics would be a faster and cheaper way to monitor the water treatment system, how effective it is working and which specific chemicals are needed to make specific water sources potable.¹⁰ This technique also has other uses within water treatment: it would help detect if there is need for improvement in any treatment steps and would locate the source of any contamination, as well as having significant use in chemical research of how new treatment chemicals may interact with water contaminants.¹⁰ However, for this method to be used, water absorbance spectral pattern determination would be required on a very detailed and accurate basis, which requires lots of research using Aquaphotomics, which isn't yet established, as it is relatively new on the scene.⁵

Perspective 3: tackling the root cause with a circular economy approach

Even from a chemical science perspective it is important to understand that by taking a circular economy standpoint the root cause of the problem could be solved.¹¹ The root cause being the overconsumption of water, pollution of water sources and the effect of climate change on water sources.¹¹ There is a requirement for the chemical sciences to tackle any of these issues and help build the infrastructure needed to accommodate a circular economy approach.¹¹ This circular approach would also have the additional benefits of healthier ecosystems and reducing the impact of climate change, which amplifies water shortage around the world.¹²

The holistic approach (**Figure 2**) could be taken where the whole system of highly polluted water sources is considered, not just the immediate problem of requiring clean water.¹¹ This can be linked to the chemical sciences in many ways, for example, chemical contaminants of water sources, such as fertilizers and pesticides being leached into rivers and nearby water sources, these chemicals need to be developed to have improved chemical safety so that their impact on rivers and ecosystems are less affected, which requires the research by

chemical scientists.¹¹ Fewer harmful chemicals in water sources would mean less water treatment is required and therefore the impact is reduced as well as the time and money spent on the water treatment.

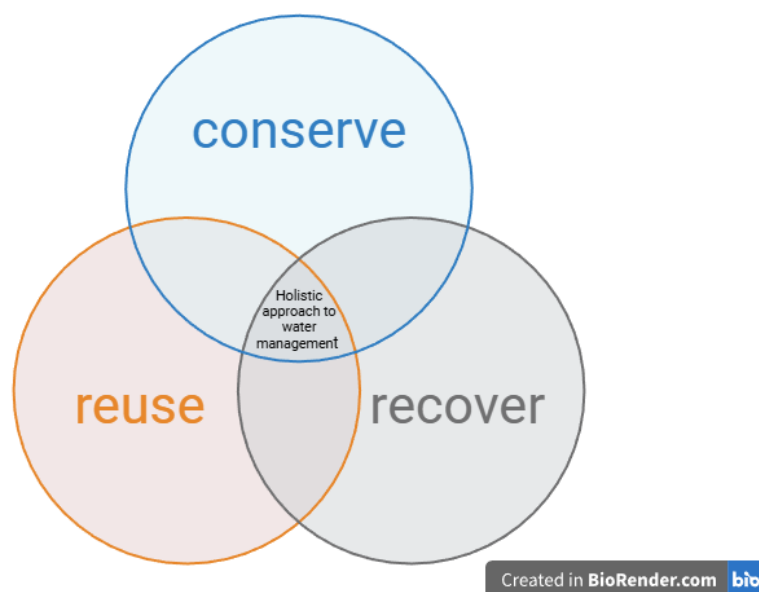


Figure 2 Figure presents the idea of 3 main elements of a holistic/circular approach to water treatment: conservation, reuse and recovery.¹²

Grey water recycling provides an example of a circular economy infrastructure.¹³ The general idea is that some domestic water is minimally contaminated after use and may be reused within the home, for example water used in a shower could be recycled to flush the toilet or irrigate the garden.¹³ This would significantly reduce water consumption and volume of wastewater produced within the average household, maximising the lifespan of resources.^{12,13} A reduction in wastewater would make treatment requirement less abundant, therefore cheaper and faster, with additional benefits to being more sustainable and environmentally friendly. However, forming this infrastructure would cost significant amounts of money as systems would have to be installed in all houses, but would be a good model for a circular approach and development of more cheaper installation options are required.¹³

Conclusions

In summary, this essay has looked at different angles in which a chemical scientist could help address some of the 17 UN sustainable development goals by 2030 linked to water availability worldwide. In the first section multiple, more sustainable and environmentally friendly methods of purifying water to produce potable water were discussed, such as use of reactive oxygen species and photocatalysis. In the second section an idea about the use of a new water monitoring and testing method (Aquaphotomics) was discussed, including its potential to reduce the use of chemicals and further the understanding of water and how it interacts with different chemicals and contaminants. This further development of understanding waters interactions links to the third section where the example of developing safer, less toxic chemical solutions that are less harmful to the environment and less likely to contaminate water sources.¹¹ In the third section a slightly different perspective was taken, looking into how a circular economy approach could deliver the sustainability of water treatment and how tackling root causes, including water pollution and climate change, could be the answer to a sustainable production of potable water. The topics discussed across these three sections mainly link to the following UN sustainable development goals: (1) “Ensure sustainable consumption and production patterns”, (2) “Take urgent action to combat climate change and its impacts” and (3) “Conserve and sustainably use the oceans, seas and marine resources”.¹⁴

Statement on use of AI

No use of AI was used in the production of this essay.

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Finalist

The lithium paradox: how (electro)chemical sciences can protect the water we risk to power the future

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In my laboratory, I work with an element that promises to power the future. Outside my laboratory, the same element is quietly drying up the water sources of Atacamenno and Aymara indigenous communities in South America's Lithium Triangle.¹ Its reach does not stop at the mine's edge but extends into the drinking water supplies far beyond.

The global energy transition has thrust lithium into the spotlight. Once an element that spent most of the 20th century in medicine cabinets is now the beating heart of every electronic gadget, electric vehicle battery, and most grid-scale storage systems. To meet the projected demand, lithium production must increase five-fold by 2050, and the overwhelming majority of that lithium will be pulled from salt-flat brines in some of the world's most water-stressed landscapes.² But the paradox runs deeper than extraction. Once released into the environment, lithium finds its way back into drinking water through industrial runoff, battery disposal, and residual brine discharge, where emerging epidemiological evidence now links it to neurodevelopment harm in children even at sub-therapeutic concentrations.³ In other words, we face a problem born of chemistry that only chemistry can resolve. The key question becomes: How do we secure the lithium that powers a clean future without poisoning the water that sustains all life? As an electroanalytical chemist, I work daily with the very tools that could help resolve this paradox. Lithium-selective electrodes and electrochemical intercalation materials, I will argue, offer the chemical sciences a veritable closed-loop solution.

Electrochemical intercalation offers a fundamentally different approach to lithium extraction than the evaporative methods that dominate the industry today. Intercalation host electrodes, materials capable of selectively accommodating Li⁺ ions within their crystal lattice, capture lithium from brine through a reversible electrochemical mechanism.⁴ This process is driven by an applied electrical potential rather than months of solar evaporation. To appreciate why this matters, one must first understand the scale of the problem it addresses. Conventional evaporative brine processing pumps lithium-rich brines from underground aquifers into vast open-air evaporation ponds, where solar energy slowly concentrates the brine over 12 to 18 months.⁵ The process consumes approximately two million liters of water per tonne of lithium produced, in a desert that receives less than one millimeter of rainfall annually.⁶ As such, the consequences are not abstract; satellite images of the Atacama Salar document a measurable retreat of wetland boundaries over the past two decades.⁷ Electrochemical intercalation sidesteps these harms entirely. It requires no evaporation ponds and can be powered by renewable electricity. The process exploits the geometric and charge-density constraints of the host lattice to preferentially select Li⁺ over competing ions such as Na⁺, K⁺, and Mg²⁺. Furthermore, electrochemical intercalation operates through repeated capture-and-release cycles without the land and water footprint of conventional ponds. Pilot-scale demonstrations have confirmed the technical feasibility of this approach,⁴ yet challenges remain in electrode longevity, brine variability, and cost competitiveness. These are precisely the problems that the chemical sciences community is best positioned to solve.

Solving the extraction problem, however, addresses only one side of the paradox. For lithium already present in the water streams, chemists must offer an equally robust solution for detection and monitoring. Unlike contamination from industrial point sources, lithium in drinking water is difficult to attribute and currently unregulated. The United States Environmental Protection Agency (EPA) has yet to establish an enforceable maximum contaminant level for Li⁺ in drinking water and no international guideline value exists from the World Health Organization (WHO). In the absence of binding standards, real-time monitoring becomes the first and most critical line of defense. Yet, the most commonly used techniques for lithium detection, inductively coupled plasma optical emission spectrometry (ICP-OES) and flame photometry, are lab-bound, expensive, and inaccessible to the communities most at risk. For instance, a rural village in northern Chile situated downstream from an active lithium brine operation has no practical means of testing its own water supply using these

methods. This is not merely an inconvenience; it is structural inequity that leaves the most exposed populations with the least information about their own exposure.

Ion-selective electrodes (ISEs) with lithium-selective ionophores offer a compelling alternative. These electrochemical sensors exploit the selective binding affinity of ionophore molecules, such as the widely studied ETH 1810 compound, embedded within a polymeric membrane to generate a measurable electrochemical potential proportional to the lithium concentration in solution.⁸ The resulting devices are low-cost, portable, and capable of real-time potentiometric measurements without complex laboratory infrastructure. Crucially, ISE platforms can be automated and miniaturized for deployment in field settings, enabling water quality surveillance at or near the region of concern. Advances in solid-contact ISE architectures have further improved long-term stability and reduced the need for frequent recalibration, which is a practical requirement for deployment in resource-limited environments.⁹ Taken together, the convergence of cleaner extraction and accessible monitoring can transform isolated scientific advances into a coherent, deployable response to the lithium-water crisis.

The lithium paradox is not without resolution: the chemical sciences already hold the foundational tools; what is needed now is the policy architecture to bring them to scale. Three actions can accelerate sustainable access to clean water for all needs. First, governments should incentivize the transition from evaporative brine processing to electrochemical extraction through targeted procurement standards and research funding. Second, the EPA and WHO should boost the establishment of enforceable guideline values for lithium in drinking water, drawing on the growing body of epidemiological evidence linking chronic low-level exposure to neurodevelopment harm. Without regulatory anchors, monitoring efforts lack the reference points needed to trigger meaningful public health responses. Third, international development programs should fund the deployment of ISE-based water monitoring in the Lithium Triangle and emerging extraction frontiers, placing analytical tools directly in the hands of those most affected. These are not utopian proposals. Electrochemical intercalation has been validated at pilot scale, ISE-based sensors have been deployed for water quality monitoring (for e.g., nitrate and fluoride surveillance) in resource-limited settings, and the regulatory infrastructure for drinking water contaminants already exists and can accommodate lithium with sufficient political will. The chemical sciences community has a responsibility not only to develop these solutions but to advocate for the conditions under which they can be deployed equitably. Clean water and clean energy are not competing priorities, but without deliberate intervention the pursuit of one will continue to come at the expense of the other.

The energy transition will proceed regardless of whether its cost on water purity is addressed. Whether it proceeds justly is a question that the chemical sciences are uniquely positioned to influence. The analytical and electrochemical tools described above represent a starting point rooted in scientific foundation upon which equitable, evidence-based water policies can be built. Overall, a discipline with the analytical precision to detect lithium at parts-per-billion resolution bears an equal responsibility to deploy that precision not only in advancing the energy transition, but in safeguarding the water systems upon which all other transitions ultimately depend.

Statement on use of AI

Use of Artificial Intelligence (AI): No AI was used in the preparation of this essay.

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Finalist

The glass is half full: the beauty of water chemistry as a guide to green design

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I once found myself arguing with Paul Anastas about green chemistry at a Gordon Research Conference. Warner, one of the founders of the field, his co-author, had just stated during a discussion that there was no area of chemistry where green chemistry could not be applied. If someone believed otherwise, he added bluntly, they were wrong. And the remark irritated me. I thought that science should leave room for uncertainty, and later that evening, in the informal honesty that conferences (and perhaps a *few* drinks) sometimes encourage, I told him so. Looking back, there were probably too many drinks involved, but our disagreement was probably less about whether green chemistry can be applied everywhere and more about what it means *to apply* it at all. If water sustains life through its remarkable chemistry, then perhaps green chemistry must begin by learning how not to work against it. And if so, we are left with a more difficult question: is it enough to develop better ways of cleaning water, or must we also redesign the chemistry that determines what enters it in the first place?

Green chemistry itself is often introduced as a set of principles: safer solvents, fewer by-products, and improved atom economy.¹ However, its deeper implications are far more radical, as they demand that chemists rethink the design of chemical systems from the beginning. Instead of developing molecules first and managing their environmental consequences later, green chemistry challenges us to design reactions that are compatible with the natural systems in which they operate.

Few substances, I believe, illustrate this idea more *clearly* than water.

Water is often treated as a simple, abundant, polar, and, at the end of the day, convenient resource. However, at the molecular level, it behaves in extraordinary ways. Each molecule participates in a constantly shifting network of hydrogen bonds, like a beautiful dance, forming and breaking connections on a picosecond timescale.² This dynamic structure governs molecular interactions in aqueous environments, and hydrophobic moieties disrupt the hydrogen-bond network, forcing the surrounding water molecules into ordered cages that reduce entropy. Nature responds – it always has a way of responding – by minimizing that ordering: hydrophobic molecules aggregate, polymer chains collapse, and molecular assemblies spontaneously form. Meaning entropy, in other words, quietly governs the behaviour of chemistry in water. This phenomenon, known as the hydrophobic effect, is responsible for some of the most fundamental structures in nature.³ Proteins fold because hydrophobic amino acids retreat from water into compact core structures. Biological membranes are formed when amphiphilic lipids self-assemble into bilayers. Even complex supramolecular structures emerge from the same simple principle: water organizes molecules according to their interactions with the hydrogen-bond network. In this sense, water does not merely partake in chemistry; it organizes our way of being.

Once this perspective is recognized, the implications for sustainability become profound. If water acts as a molecular organizer, then chemistry can be designed to work with its intrinsic logic rather than against it; and this idea has quietly begun to reshape several areas of chemical science, as it strongly tackles one of the most pressing global goals of our time: ensuring sustainable access to clean water (a priority recognized by the United Nations Sustainable Development Goal 6).^{4,5} But again, we must ask: is it just a resource to be treated and recovered? In micellar catalysis, surfactants assemble in water to form nanoscale reactors with hydrophobic interiors, concentrating organic molecules and accelerating reactions that would otherwise require organic solvents to proceed.⁶ In atmospheric chemistry, cloud droplets function as microscopic chemical reactors in which dissolved gases undergo oxidation, regulating planetary cycles.⁷ In materials science, amphiphilic molecules spontaneously assemble into vesicles, membranes, and nanostructures under the influence of water.⁸ Across scales, from biological macromolecules to atmospheric processes, water acts as a powerful molecular architect.

Portuguese chemist José Teixeira Dias captured this idea in an unusual way. His physical chemistry textbook begins with water molecules and ends with the liquid itself,⁹ achieving something extraordinary where the

structure of the book mirrors the remarkable journey from simple molecular geometry to the collective behaviour of one of nature's most complex liquids. Only a small set of substances illustrate so clearly how microscopic interactions give rise to emergent chemical phenomena and, once we understand that this emergence is not merely an intellectual exercise, we can use it to guide the design of sustainable chemistry as we consider the sustainability challenges (environmental, social and economic) of our time.

Modern plastics are often resistant to degradation because their structures are designed without considering the environments in which they ultimately accumulate. Yet, by rethinking reaction environments, it is possible to create systems in which water actively participates in the chemical degradation of polymers under mild conditions.¹⁰ And we now see a movement, an exploitation of water not only as a consumable but also as a reactive – and creative – environment capable of transforming pollutants and enabling cleaner processes in many other areas of chemistry.¹¹ Advanced oxidation processes generate highly reactive hydroxyl radicals directly in water, breaking down persistent contaminants, such as pharmaceuticals and pesticides;¹² photocatalytic materials harness light to produce reactive species that degrade organic pollutants,¹³ whereas electrochemical treatments use electricity to drive purification reactions without chemical additives;¹⁴ in parallel, new porous materials and membrane technologies have been developed to selectively remove contaminants, ranging from heavy metals to persistent fluorinated compounds, further enabling the circularity of water.¹⁵ In unison, these approaches illustrate a broader lesson: when chemical processes are designed with water in mind, the same molecular principles that govern chemistry in nature can also help preserve water quality in the environments where chemistry operates. The effectiveness of such systems does not arise from any single powerful component but from the way the reaction environment aligns with the thermodynamic tendencies of this extraordinary molecule.

Physicist Paul Dirac once suggested that beauty can guide scientific discovery – that the most fundamental equations in physics often possess an intrinsic elegance that hints at their truth.¹⁶ Chemistry rarely exhibits the same mathematical symmetry, but it sometimes reveals a comparable form of thermodynamic elegance: processes that cooperate with natural molecular forces, such as entropy increase, hydrogen bonding, and phase separation, often succeed where more forceful strategies fail. In sum, the elegance of these approaches lies in their simplicity.

But there is a danger in admiring our ingenuity too much – and reaching elegant solutions should not make us complacent. The same chemical sciences that can detect, degrade and remove pollutants often do so only after water has already been burdened by them.¹⁷ And every remedy carries its own demands: energy to power it,¹⁸ materials to sustain it,¹⁹ infrastructure to deploy it,²⁰ and institutions and policy makers to make it available beyond the laboratory – especially those that can help point us toward fixing affordability, scale, reliability, agriculture, industry, sanitation, and regional inequalities.²¹ From municipal treatment plants to decentralized rural systems; from industrial discharge to drinking water infrastructure; across regions where access remains uneven: clean water, then, is not secured by technical cleverness alone. It depends on whether chemistry can move from correction to foresight. Green chemistry, at its best, is the art of designing chemical systems that cooperate with these natural forces, and providing sustainable access to clean water will undoubtedly require new purification technologies, improved infrastructure, and advances in materials science. But the deeper challenge may lie upstream in the design of chemistry itself: *the cleanest water-based technology, after all, may be the chemistry that never contaminates water in the first place.*

Sometimes, I think back to that conversation at the conference. Perhaps Warner's remark was not a declaration of certainty, but a challenge. If green chemistry is truly applied everywhere, it may be because it is not a specialized subfield. It is simply chemistry practiced with an awareness of the systems that sustain life: a philosophy of practice – learning not merely how to purify our most valuable resource, but how to design processes that work with it from the very beginning.

In that sense, *the glass is half full*. Not because the work is finished, but because the tools, the knowledge, and the responsibility are already within reach. There is still much left to fill – but what remains is no longer uncertainty, it is choice. And few things in life remind us of this responsibility more *clearly*.

Statement on use of AI

AI was used in the preparation of this essay to improve grammar, clarity, readability, and formatting compliance. No AI tool was used for the initial drafting or primary writing of the essay, for producing scientific insights, analysing or interpreting data, drawing conclusions, or creating figures or tables. The author reviewed and edited all text and accepts full responsibility for the accuracy, originality, and content of the submission.

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Finalist

***Contaminants of emerging concern: cheaper, easier,
cleaner removal for clean water through chemical sciences***

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Introduction

According to the United Nations' sixth Sustainable Development Goal (SDG), investments in infrastructure and sanitation facilities are necessary to ensure universal access to safe and affordable drinking water by 2030. Nevertheless, chemical contamination of water remains a global issue affecting millions of people. Around 2.1 billion people still lack access to safely managed water despite efforts made from 2015 through 2024.¹ A publicly recognized contaminant is plastic, whose effects are more noticeable than micro-scale wastes. However, many people overlook the risks of another dangerous chemical substance group, per- and polyfluoroalkyl substances (PFAS), which encompasses over 4,730 chemicals.² PFAS are introduced in water ecosystems through sources from agricultural irrigation, application of biosolid fertilizers and industrial processes.³ Considering the increasing prevalence of these contaminants of emerging concern and the urgency to develop mitigation strategies, this essay aims to highlight the potential of an adsorption and advanced oxidation process (AOP) combination strategy for PFAS treatment to achieve sustainable access to clean water at a global scale.

Adverse effects of PFAS contamination of water

PFAS have been used for decades in nonstick and water-resistant products, such as Teflon and waterproof fabric. Due to their persistent organic structure with strong C-F bonds, PFAS are non-biodegradable. PFAS have been found in crops, water, and soil, and can be taken up by edible plants, leading to transfer and accumulation throughout the food chain.⁴ The toxic and persistent nature of PFAS also drives health conditions, including cancer, thyroid hormone disorders, and reproductive dysfunction.^{5,6,7} Emerging international concern about the potential for PFAS bioaccumulation has pushed major manufacturers to phase out the production of some PFAS substances – perfluorooctanesulfonic acid perfluorooctanoic acid – in the early 2000s. However, these compounds were replaced by others, like perfluorobutanesulfonic acid and GenX. Since the early 2000s, laws, policies, and regulations have been implemented to reduce the prevalence and exposure of PFAS to the ecosystem.⁸ Yet innovative technologies are needed to detect and treat PFAS because traditional water treatment methods are insufficient to remove them.

Current Removal Technologies

Remediating PFAS contamination is a complex and challenging task. Traditional methods are often ineffective in removing PFAS due to their persistence and mobility.⁹ To overcome these limitations, several new treatments have been developed in the past decades. Among those various removal technologies, adsorption is seen as the most prominent and applicable method. It is relatively simple and generally does not involve the addition of chemical agents, making it less environmentally damaging.¹⁰

Adsorption: Adsorption is a physical treatment method that involves transferring PFAS from water to a solid surface through interactions between the highly porous adsorbent surface and the molecules. Contaminants are physically transferred by Van-der-Waals forces when a PFAS molecule binds to the surface of the adsorptive media.¹⁰ Activated carbon is an effective adsorbent due to its highly porous structure that provides a large surface area. Granular activated carbon and anion exchange resins are also frequently used adsorption removal materials due to their financial availability.^{5,8} However, this method has some limitations. First, the adsorption capacity of the substances is governed by factors such as temperature, pollutant concentration, and pH; consequently, adsorption efficiency can decrease due to changes in these parameters.⁵ Also, when the adsorption sites fill, they need to be replaced and disposed of, while adsorbent regeneration requires thermal or chemical processes. These requirements may produce hazardous chemicals such as fluorine gases.¹¹ Secondly, adsorption mechanisms don't eliminate PFAS from the environment; they only concentrate the toxic contaminants on adsorbent surfaces, creating solid waste. Moreover, as Nakazawa et al. demonstrated,

adsorbents like GAC can't efficiently adsorb short-chain PFASs, suggesting potential compromises in long-term efficacy.⁸

Nevertheless, adsorption removal still remains the most promising approach because it is widely studied, financially available, easy to implement, and offers combinations with other removal methods like advanced oxidation processes (AOPs)

Electrochemical oxidation: Electrochemical oxidation (EO) is an AOP that utilizes an electrical current within an electrolytic cell containing an anode and cathode submerged in a conductive solution to break down PFAS molecules into less harmful components.⁸ EO oxidizes pollutants via in-situ electro-generation of powerful oxidants (particularly the hydroxyl (OH) radical) where only an electron is formed during the treatment.¹² Thus, EO provides an environmentally friendly alternative. It can function at ambient temperature and atmospheric pressure, without the addition of harsh chemicals and without producing secondary waste.¹³ Moreover, EO has been successfully applied for on-site treatment of industrial effluents, landfill leachates, and groundwater, demonstrating notable efficacy in degrading short-chain PFAS.¹⁴ Despite high removal effectiveness, electrode fouling, high energy requirements, and the formation of toxic byproducts pose challenges for the widespread use of this approach.^{11,14} To address these limitations, self-cleaning electrodes and optimized operational parameters that improve energy efficiency and reduce byproduct generation are needed.^{11,15}

Employing combined treatment to meet accessibility needs

To achieve a cost-effective, environmentally benign, and energy-saving treatment that minimizes waste (**Figure 1**), a hybrid approach of adsorption followed by the reduction-oxidation method can be embraced. Adsorption can function as a pretreatment, collecting the PFAS and concentrating it for further processes. Then, the concentrated PFASs can be better degraded using EO. Thus, the initially problematic property of the adsorption method becomes advantageous.^{6,10} Furthermore, adsorbents like activated carbon were shown to lower the concentration of halogenated byproducts of EO, offering a solution to toxic byproduct generation.¹³ Possible combinations involving the use of AOPs and different adsorption processes can develop cost-effective methods that would enable widespread treatment of PFAS in disadvantaged communities. However, technological innovations are not enough to fully resolve the water contamination issue due to limitations in social and economic aspects.

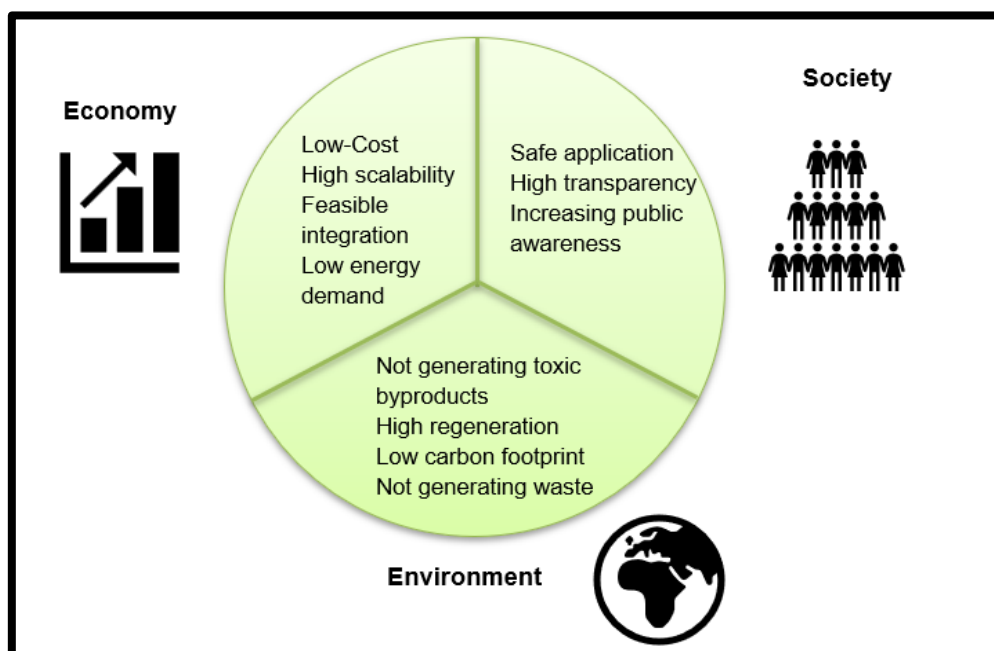


Figure 1 Sustainability dimensions for optimum PFAS treatment technologies considering environmental, economic, and social factors (Figure constructed using Microsoft Word)

Political, financial, and social limitations and remedies

Despite the notable innovations in detection techniques and remediation technologies, challenges remain in monitoring PFAS contamination. Focusing on each PFAS one by one is neither feasible nor cost-efficient. To address the issue holistically, PFAS have to be managed as a class. Limiting the entire class of PFAS to "essential uses" (as defined by the Montreal Protocol in 1987) is the best approach to eliminate the source of pollution.¹⁶

The main challenges are: unclear lines of regulatory authority, insufficient funding, incomplete scientific evidence, and practical challenges.² Hence, simpler, cheaper, more comprehensive, and more class-based universal solution efforts are needed to improve the removal and detection of emerging risks. Infrastructure investments and funding to address emerging contaminants, such as those announced by the U.S. Environmental Protection Agency in February 2023, would promote access to safe and clean water in small, rural, and disadvantaged communities while supporting local economies.⁷

Fundamentally, regulation and management policies can only function if all environmental, social, and economic aspects are considered. Therefore, increasing social awareness and recognizing marketplace benefits as well as environmental impact is essential for sustainability. Promoting regulatory action for PFAS as a class can adequately be implemented as it can reduce financial disadvantage in the industry by encouraging innovations towards safer alternatives.¹⁶

Conclusions

PFAS contamination of water poses significant environmental and health risks due to their toxic and persistent nature. At present, treatment strategies of PFAS in industrial wastewater and drinking water are still dominated by physical treatment methods such as activated carbon and anion exchange resin adsorption. The disposal problems and high cost of regeneration drive the development of PFAS-specific technologies. The combined-treatment approach is a feasible and advantageous strategy to mitigate PFAS contamination of water, as it can achieve high efficiency with lower energy consumption. Though many of the emerging technologies haven't been implemented at full scale, necessitating in-site experiments to make a comprehensive review.^{11,17} Considering that current remedies have only been developed in the last two decades, they have limited data on the long-term environmental impacts and life cycle assessment of these technologies.^{15,18} In future investigations, field applications and carbon emission of the possible treatments should be examined to achieve sustainable water treatment without environmental pollution. Finally, to hasten the application process, fundings in remedies such as Weaver Lab's Flor-mop technology are essential to enable chemical sciences to perform the best.¹⁹ Infrastructure investments to facilitate water treatment services in rural areas are necessary to ensure accessibility and safety of water.²⁰ In addition to removal, detection of contaminants also poses huge challenges, which should be addressed. Adsorption-based electrochemical mechanisms are also possible advanced field-detector candidates due to their high sensitivity.²¹ Ultimately, when combined with policy regulations, adsorption-decomposition combination treatment strategies carry a high potential to efficiently remove PFAS to facilitate sustainable access to clean water at a global scale.

Statement on use of AI

In the preparation of this essay, Grammarly was used to enhance the clarity and language of the text. After using this tool, the author reviewed and revised the content as required, taking full responsibility for the final publication.

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Finalist

From pollution to regeneration: redefining wastewater in the age of water bankruptcy

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The world has entered the era of global water bankruptcy, in which freshwater resources are rapidly depleting while demand continues to rise.¹ Once a speculative concern, the question raised in Rudy Francisco's poem "*When The Water Is Gone*" has become increasingly relevant: will future generations experience water the same way as we do today, given the ongoing water scarcity? Indeed, global lakes have declined by 53%,² groundwater by 30%,³ and 364 river basins have been permanently lost,⁴ driven by massive population growth and climate change. This water crisis will threaten livelihoods, increase poverty, prolong illnesses, cause vulnerability, and lead to conflict.¹ Consequently, addressing this crisis must be an urgent global priority to sustain life. Chemical science offers a promising solution by providing technologies that transform wastewater into a new source of clean water. The enormous volume of wastewater (2,100 trillion liters per year) represents a significant untapped potential.⁵

Over the years, conventional wastewater treatment methods, including physical and mechanical processes, have achieved a certain degree of effectiveness. However, these systems fail to remove contaminants of emerging concern (CECs) from wastewater, including nutrients, heavy metals, endocrine disruptors, pharmaceuticals, microplastics, and per- and polyfluoroalkyl substances (PFAS).^{6,7} Moreover, large-scale infrastructure and space requirements constrain their suitability in densely populated areas.⁶ At the same time, the wastewater treatment plant (WWTP) has traditionally been designed only to treat wastewater to release it back into the environment. Rethinking their role, it would be more beneficial to design WWTPs as integrated systems that simultaneously monitor, treat, and distribute water. This approach would pave the way for a truly functional, next-generation WWTPs. Realizing this vision, however, depends on advanced treatment methods that can reliably produce safe, clean water for reuse. **Figure 1** illustrates advanced methods emerging from chemical science for wastewater treatment.

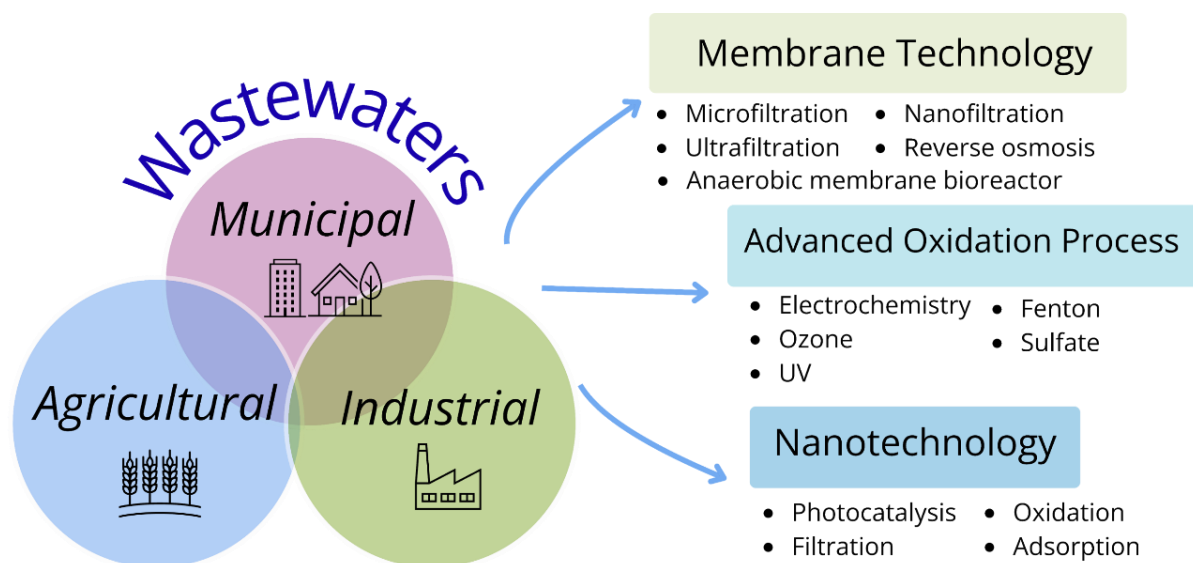


Figure 1 Advanced chemical methods used in wastewater treatment to produce clean water

At the forefront of this transformation, chemical science is improving WWTP performance by developing multiscale materials for membrane technology, including microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF). Membrane technology is widely used to treat various wastewater streams, including industrial, municipal, and agricultural wastewater.^{6,8} It primarily separates pollutants based on their transport rates, particularly size. For instance, MF can separate dissolved solids, turbidity, and microorganisms. UF can separate pathogens, macromolecules, and suspended particles. NF, in turn, can remove monovalent ions, organic groups, and divalent ions.⁸ Collectively, these processes have demonstrated strong potential in removing CECs, such as pharmaceutical and endocrine disruptors.⁹ This technology has been successfully implemented in Singapore's NEWater, turning wastewater into drinking-quality water that supplies nearly 40% of the country's water needs (760 million litres/ day).^{6,8,10}

Beyond water recovery, advanced membrane technologies, such as anaerobic membrane bioreactors, enhance sustainability by simultaneously removing pollutants and producing biogas from the breakdown of organic matter. Previous research reported that this method can achieve 90% removal of chemical oxygen demand (COD) and produce 0.29 litres of methane gas per gram of COD degraded.¹¹ The produced biogas is usually used as an energy source within the WWTP.¹² This offers simultaneous pollutant reduction and energy production, promoting wastewater circularity and economic growth. Although membrane technology offers dual benefits, it produces toxic sludge that poses health and environmental risks.⁶

The advanced oxidation process excels at oxidizing toxic pollutants into harmless substances, making it highly environmentally friendly. It is effective for degrading CECs from water, including pharmaceuticals, antibiotics, and endocrine disruptors. It is also a flexible, easy-to-customize system that simplifies installation. Therefore, it is widely used to treat industrial wastewater streams containing numerous toxic pollutants. The advanced oxidation process uses hydroxyl and sulfate radicals to oxidize pollutants, generated via electrochemistry, ozone treatment, ultraviolet-catalysed titanium oxide, and Fenton reactions.^{7,9} It was successfully implemented in California's direct and indirect potable reuse water facilities and is planning to reclaim 1.8 million acre-feet of water by 2040.^{13,14}

The contribution of chemical science is continuously evolving. A notable recent development is the use of nanomaterials.⁶ Nanomaterials possess large surface areas that enhance reactivity and catalytic performance in pollutant removal, which can be used in combination with photocatalysis, filtration, oxidation, and adsorption for enhancing wastewater treatment.¹⁵ This technology shows high potential in removing CECs, including heavy metals, dyes, pharmaceuticals, antibiotics, and PFAS.^{9,15,16} However, their real-world application is still challenging; once sufficiently developed, nanomaterials provide a high-performance yet environmentally friendly wastewater treatment solution.

Chemical science has advanced methods for WWTPs, providing an effective means of removing harmful pollutants. The next challenge is to determine "How can WWTP performance be further enhanced to achieve water sustainability?" This is where remote sensing provides a solution. Remote sensing is the science of gathering information about objects, areas, or phenomena using non-contact devices like satellites and drones.¹⁷ It offers a sophisticated tool for monitoring water quality, planning WWTP installations, and managing treated water distribution. Remote sensing enables non-contact water-quality monitoring by analysing pollutant reflectance.¹⁷ Although it may appear to replace chemical science in pollutant detection, it is an extended form of chemical science in sensor technologies.

Recent advances in chemical instrumentation have enabled the measurement of spectral signatures of water-quality parameters. These spectra are then connected to image data via algorithms. Once this algorithm is established, remote sensing can be used to monitor water-quality parameters.^{17,18} This development process was exemplified by the study of the identification of urban water pollution sources. Initially, the fluorescence spectra of dissolved organic matter from 337 polluted water samples were measured using three-dimensional excitation-emission matrix fluorescence spectroscopy. Then, fluorescence data were analysed using hierarchical clustering and several algorithms to establish remote sensing-based monitoring, thereby enabling rapid assessment of urban water pollution.¹⁹ Compared to traditional in-situ monitoring, which is often time-consuming, labour-intensive, and has limited sampling coverage, remote sensing allows for fast, real-time, large-scale, and long-term water quality monitoring.¹⁸

Recently, remote sensing has emerged as a promising approach for detecting CECs in water. Microplastics were detected using the infrared hyperspectral imaging satellite (HIS),²⁰ *Salmonella* and *Vibrio* were detected using Sentinel-2 satellite imagery.²¹ Heavy metal concentrations were successfully quantified using the Chinese Huan Jing-1A HIS, resulting in detection limits of <0.15 mg/L for copper and <0.001 mg/L for cadmium. Detecting PFAS remains difficult; however, employing optical, fluorescence, and Raman spectroscopy may facilitate remote sensing.^{22,23} These advantages can be used to quickly monitor water quality after each treatment stage, particularly using ground-based remote sensing, which enables assessment within a closed WWTP facility.²⁴ By

doing so, monitoring in WWTPs could be accelerated, making quality control easier and speeding up clean water distribution. This approach also offers an environmentally friendly alternative for monitoring technology, enabling pollutant detection without hazardous solvents. **Figure 2** illustrates how advances in remote sensing support chemical science in the design of a sustainable WWTP.

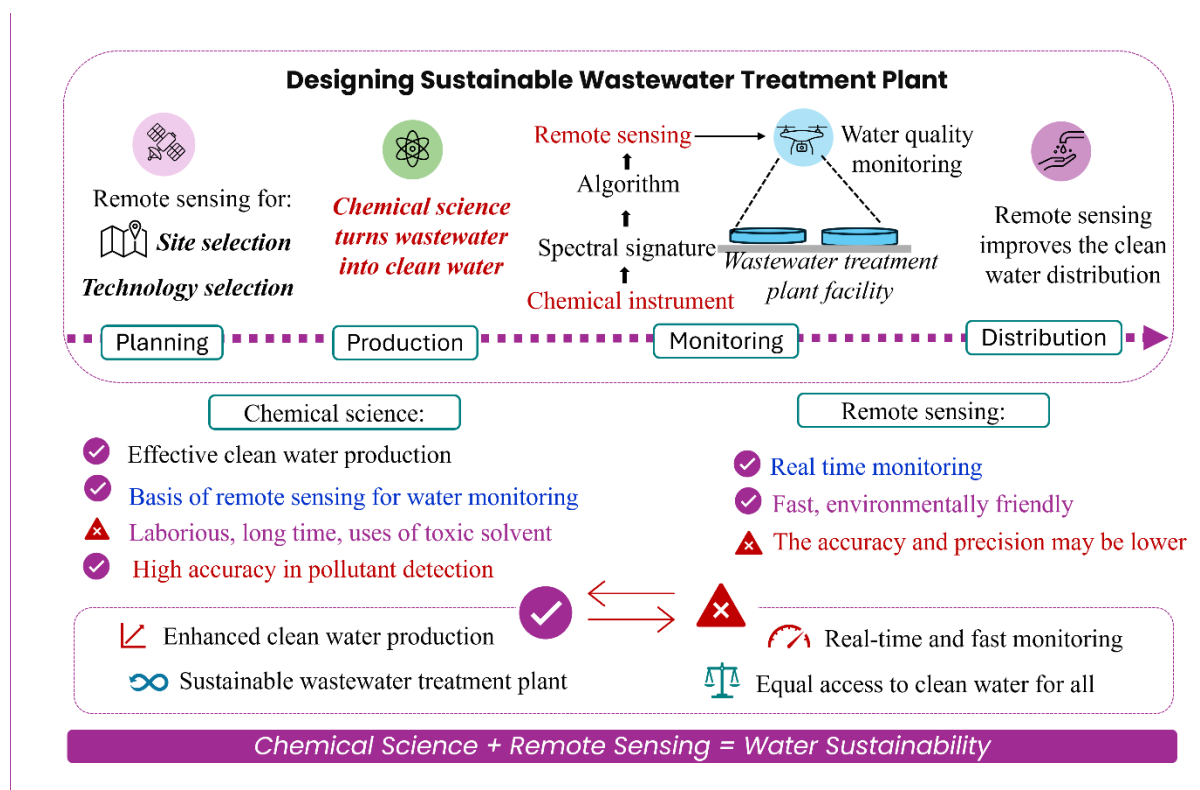


Figure 2 Chemical science and remote sensing support and complement each other to improve WWTP performance and promote water sustainability

Moreover, remote sensing has also assisted in selecting WWTP locations, as has been done in India and Cambodia. It streamlines the analytic hierarchy process for planning, enabling the reduction in the number of WWTP facilities and the expansion of wastewater coverage while accounting for socio-economic factors.^{25,26} Inspired by this, future remote sensing can be functionalized to quickly determine which technology or method is suitable to install in a WWTP. This can be accomplished by initially tracking wastewater flows, pinpointing their sources, and uncovering potential pollutants entering the WWTP. Moreover, residual pollutants from past anthropogenic activities can also be detected by remote sensing.¹⁷ Thus, the appropriate WWTP technology can be selected based on the existing pollutant group to be treated, enabling appropriate, fast, and high pollutant removal efficiency, preventing long-term contamination, and safeguarding public health.⁹

Beyond WWTP design, remote sensing also provides additional benefits for broader water management. It can identify sources of both fresh and contaminated water that remain underutilized, especially in uncharted areas.²⁷ As a result, it will provide strategic insights for stakeholders when installing new WWTP facilities, thus increasing the water management effectiveness. Lastly, remote sensing supports the development of distribution strategies for treated water in uncharted areas by visual mapping.²⁸ It possibly enables water to cross geographical boundaries, promoting fair and inclusive access to clean water across regions and nations.

Together, chemical science and remote sensing complement each other in achieving water sustainability. Production, monitoring, treatment, and equitable distribution of clean water can be achieved rapidly and simultaneously. However, several challenges may arise: first, the diverse types of pollutants in wastewater demand more advanced treatment methods. Using nanomaterials is a promising solution; therefore, efforts to implement them in real-world settings should be accelerated. Second, trace concentrations of toxic pollutants remain difficult to monitor with remote sensing. This requires collaboration among chemists, geographers, and sensor experts to develop robust and rapid remote sensing-based monitoring systems.²⁹ Third, decentralized regions may face difficulties in adopting this system due to their distinct geographical characteristics and policies. Consequently, universal and comprehensive policies on WWTPs and reused water must be established.

Establishing this WWTP requires genuine collaboration, supportive policies, and funding. The government, investors, and society must actively support its implementation. Effort towards this sustainable WWTP installation is a worthwhile investment. By promptly and more sustainably generating a water revenue stream, this WWTP can ensure water sustainability for our blue planet and future generations.

Statement on use of AI

AI was used in the preparation of this essay to improve readability and grammar. It was not used in producing scientific insights or drawing scientific conclusions in this essay.

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Finalist

***“Prevent where we can, adapt where we must”:
chemical strategies for sustainable access to clean water***

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Introduction

Despite decades of innovation in water treatment technologies, sustainable access to clean water remains a persistent global challenge. An estimated 2.1 billion people continue to lack reliable access to safe drinking water,¹ while increasing industrialisation and urbanisation introduce ever more complex contaminants into aquatic systems, including pharmaceuticals² and microplastics.³ These trends expose a fundamental limitation in how the chemical sciences have traditionally addressed water sustainability: a systemic reliance on treating contamination after it occurs, rather than preventing it at source.

Conventional approaches, ranging from membrane filtration^{4,5} to advanced oxidation processes,^{6,7} have achieved notable technical success in removing contaminants. However, their widespread implementation is often constrained by high energy demands, infrastructure requirements, and operational costs, limiting their accessibility in low-resource and decentralised settings. As a result, progress in water purification has not translated into equitable or sustainable access at a global scale. This disconnect highlights a critical need to rethink the role of chemistry, not merely as a tool for remediation, but as a driver of systemic change.

This essay argues that ensuring sustainable access to clean water requires a dual transformation in the chemical sciences: first, a shift from reactive treatment to the prevention of pollution through molecular and materials design; and second, the development of decentralised, context-specific solutions tailored to diverse socio-economic and environmental conditions. By integrating these approaches, chemical science can move beyond mitigating symptoms to enabling long-term, equitable water sustainability.

Limits of current chemical approaches

The chemical sciences have long played a central role in advancing water purification technologies; however, their prevailing paradigm remains fundamentally reactive. Contemporary treatment systems are designed to remove contaminants after they have entered water supplies, rather than addressing their sources. While such approaches have delivered substantial improvements in water quality, particularly in high-income regions, their benefits have been unevenly distributed and are increasingly misaligned with the scale, complexity, and global distribution of modern water challenges.

One critical limitation lies in the growing chemical diversity of pollutants. Traditional treatment processes were developed to target relatively well-defined contaminants; however, water systems now contain complex mixtures of pharmaceuticals, personal care products, industrial chemicals, and microplastics, many of which are persistent and poorly characterised.^{8,9} Even advanced treatment technologies can struggle to achieve complete removal or may generate transformation products with uncertain environmental and toxicological profiles.^{5,10} Highly persistent compounds such as per- and polyfluoroalkyl substances (the “forever chemicals”) illustrate this challenge, as their exceptional chemical stability makes them resistant to conventional degradation pathways.¹¹ Treatment technologies are therefore inherently constrained by the evolving diversity of contaminants they are designed to remove.

Beyond technical performance, the sustainability of these approaches is constrained by their dependence on energy-intensive and infrastructure-heavy systems. Processes such as desalination and high-pressure membrane filtration require substantial energy inputs, often derived from non-renewable sources, thereby linking water purification to carbon emissions and broader environmental trade-offs.¹² Moreover, centralised water treatment facilities depend on extensive distribution networks and continuous maintenance, making them economically and logistically inaccessible in many low- and middle-income regions.^{13,14} As a result, the benefits of advanced chemical technologies remain unevenly distributed, reinforcing existing global inequalities in water access.

Crucially, the prevailing focus on end-of-pipe solutions also fails to address the upstream drivers of water contamination. Industrial discharge, agricultural runoff, and the widespread use of persistent chemical products continue to introduce pollutants into water systems at rates that outpace remediation efforts.⁹ This creates a

cycle in which increasingly sophisticated treatment technologies are required to manage an ever-expanding range of contaminants, without reducing the underlying burden of pollution. From a sustainability perspective, this approach is inherently inefficient, as it prioritises remediation over prevention.

Taken together, these limitations suggest that incremental improvements in treatment efficiency, while valuable, are unlikely to achieve universal and sustainable access to clean water. Instead, they reinforce the need for a more fundamental reorientation of the chemical sciences, one that shifts emphasis away from solely treating contamination and towards preventing it and designing systems that are adaptable to diverse global contexts.

Prevention through chemical design

At the molecular level, this approach is embodied by the twelve principles of green chemistry,¹⁵ which advocate for the design of substances that minimise toxicity, persistence, and bioaccumulation. In the context of water sustainability, this entails developing pharmaceuticals, agrochemicals, and industrial compounds that retain their functional efficacy while being more readily degradable under environmental conditions. For example, the “European Union Strategic Approach to Pharmaceuticals in the Environment”¹⁶ aims to redesign active pharmaceutical ingredients to enhance biodegradability, as a strategy to reduce their long-term presence in aquatic systems (“benign by design”).^{17,18} Similarly, advances in polymer chemistry are enabling the development of materials that degrade into non-toxic products, addressing the growing problem of microplastic pollution.^{19,20} Such strategies shift the burden of water purification upstream, reducing reliance on increasingly complex and resource-intensive treatment technologies.

Beyond individual molecules, prevention through chemical design also extends to industrial processes and material lifecycles. The adoption of cleaner synthesis routes, solvent substitution, and closed-loop manufacturing systems can significantly reduce the release of hazardous substances into water systems.²¹ In agricultural contexts, the development of more selective and environmentally benign pesticides and fertilisers can mitigate runoff and eutrophication, which are both major contributors to water quality degradation.^{22,23} These interventions illustrate how chemical innovation can reduce contamination at its source, rather than attempting to manage it downstream.

However, the implementation of preventive strategies is not solely a technical challenge. Designing safer chemicals often involves trade-offs between performance, cost, and environmental impact, and may face resistance from established industrial practices.²⁴ Moreover, without appropriate regulatory frameworks and economic incentives, there is limited impetus for industries to prioritise long-term environmental outcomes over short-term efficiency. This underscores the need for coordinated action between chemists, policymakers, and industry stakeholders to embed sustainability criteria into chemical design and production.

Decentralised and context-specific solutions

While prevention through chemical design addresses the upstream origins of water contamination, it does not eliminate the benefits of effective water treatment systems. However, the limitations of centralised infrastructure highlight the need for a complementary shift towards decentralised, context-specific solutions that can deliver safe water across diverse socio-economic and geographic settings.

Conventional centralised treatment systems rely on large-scale infrastructure, continuous energy inputs, and extensive distribution networks, making them difficult to implement and maintain in many regions. In rural communities, informal settlements, and geographically isolated areas, such systems are often economically unfeasible or operationally unsustainable.²⁵ As a result, an estimated 4 billion people face water scarcity at some point in their lives,²⁶ despite advances in treatment technology. Addressing this disparity requires a rethinking of how chemical solutions are designed, deployed, and maintained outside of centralised frameworks.

Decentralised water treatment approaches offer a pathway to bridge this gap by enabling localised purification at the point-of-use or within small communities. From a chemical perspective, this has driven the development of low-cost, accessible materials and processes that can operate with minimal energy and technical input. For example, adsorptive materials such as biochar,²⁷ modified clays,²⁸ and functionalised polymers²⁹ have shown potential for removing organic contaminants and heavy metals in low-resource settings. Similarly, solar disinfection³⁰ and photocatalytic systems³¹ leverage abundant renewable energy to inactivate pathogens and degrade pollutants without reliance on grid electricity. These approaches demonstrate how chemical innovation can be tailored to local resource availability, rather than assuming uniform technological conditions.

However, decentralisation is not without its challenges. The long-term effectiveness of point-of-use systems depends on user acceptance, maintenance, and consistent performance under variable conditions. In some cases, technologies that perform well under laboratory conditions fail in real-world settings due to issues such

as material degradation, fouling, or lack of technical support.³² Moreover, without appropriate education and community engagement, even well-designed systems may be underutilised or misapplied.

Importantly, decentralised approaches should not be viewed as a replacement for centralised infrastructure, but as a complementary strategy within a broader, integrated water management framework. Hybrid systems that combine centralised treatment with localised purification could enhance resilience, particularly in regions vulnerable to climate variability or infrastructure disruption.³³ In this context, the role of the chemical sciences extends beyond developing new materials, to designing adaptable systems that can function effectively across diverse environmental and societal conditions.

Conclusions

Sustainable access to clean water will not be achieved by increasingly sophisticated purification technologies alone. Instead, the chemical sciences must rethink their role in two complementary ways: (i) shifting from reacting to contamination toward preventing it at its source, whilst simultaneously (ii) enabling decentralised, context-specific solutions where traditional infrastructure is limited.

By redesigning molecules, materials, and industrial processes to minimise environmental persistence, chemists can reduce the burden placed on water systems before pollution occurs. At the same time, low-cost materials and locally deployable treatment technologies can expand access to safe water in diverse social and environmental contexts. Achieving this transformation will require not only scientific innovation, but also integration with policy, industry, and society. Crucially, we must *prevent where we can, adapt where we must*.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

The blue alchemy: redefining water sustainability through chemical sciences

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Introduction

Access to clean, safe water has always been one of humanity's most urgent and essential needs, driven by an ever-expanding population, urbanization, environmental pollution, and climate change.^{1,2} These escalating pressures are expected to intensify global water stress, with approximately 57% of the total world's population projected to live in regions experiencing water scarcity for at least one month annually.³ Yet, despite being finite and indispensable to life, water is still largely governed by a linear "take-use-discharge" model.⁴ Within this framework, conventional wastewater treatment technologies have largely focused on contaminant removal, thereby "hiding" waste rather than valorizing water and nutrients.⁵ This paradigm limits the reuse, recovery, and long-term sustainability of water and must shift toward a more circular water economy.⁴ Adopted in 2015, the United Nations Sustainable Development Goals (SDGs) comprise 17 global targets, including SDG 6, which aims to ensure the availability and sustainable management of clean water and sanitation for all by 2030.⁶ In this context, chemical science offers solutions beyond mere traditional water purification, such as advanced oxidation, catalytic transformation, membrane-based separations, and mineral extraction.⁷⁻¹⁰ Together, these approaches ensure the simultaneous availability of clean water and the conversion of waste streams into feedstocks. However, to explore its actual potential, policy incentives, market development, and community engagement are equally important.¹¹

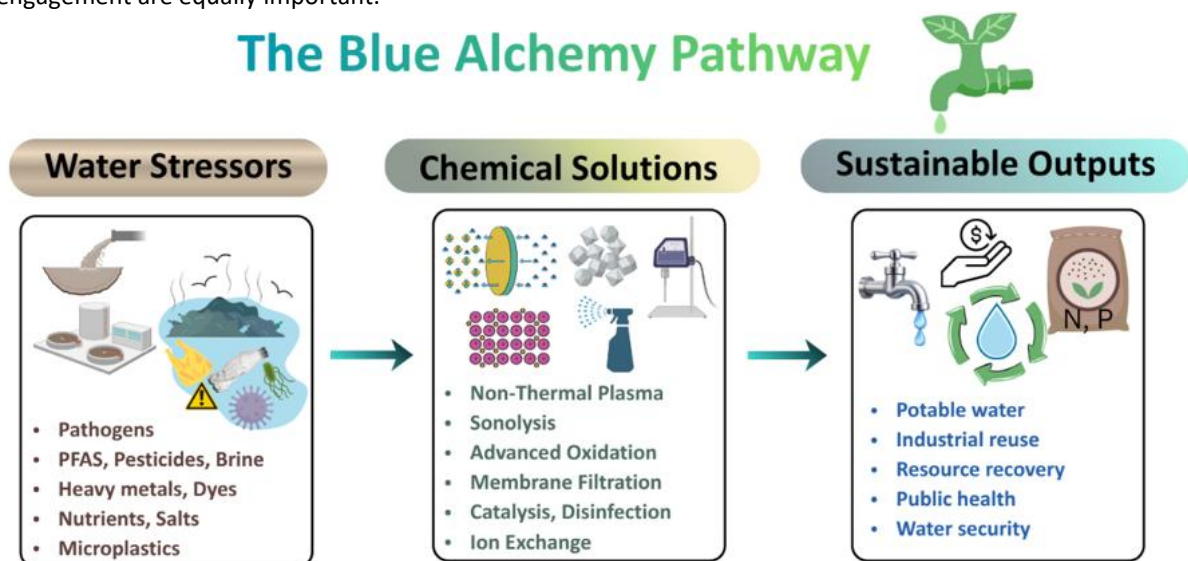


Figure 1 Schematic illustration of chemical pathways for a circular water future.

Neutralizing the indestructible

Among the most challenging emerging contaminants in modern water systems are per- and polyfluoroalkyl substances (PFAS), commonly known as "forever chemicals."^{12,13} Their exceptional chemical stability arises from strong carbon-fluorine (C-F) bonds, rendering them highly resistant to environmental degradation and water-treatment processes. This is where non-thermal plasma represents a breakthrough, degrading >90% of perfluorooctanoic acid, perfluorohexanesulfonic acid, and perfluorooctanesulfonic acid within 40 min of treatment in contaminated surface water.¹⁴ A study reported sonolysis (700 kHz) as an energy-efficient technology that completely defluorinated PFASs such as 6:2 fluorotelomer sulfonamidoalkyl betaine and hexafluoropropylene oxide dimer acid.¹⁵ Another mechanism for PFAS destruction is an activated hydroxylate-

or persulfate- based advanced oxidation system, which can attack the C–F bond and promote chain shortening, causing PFAS mineralization at lower pH.^{16,17} Together, these chemical strategies demonstrate that not only can PFAS be captured but also can be destroyed irreversibly. Henceforth, chemical engineering technologies open the door to combining plasma, sonolysis, and advanced oxidation into hybrid systems that improve both efficiency and the depth of defluorination.

Nano-crafted purity

Existing technologies for atmospheric water harvesting, disinfection, desalination, and water purification rely largely on energy-intensive physical processes such as thermal distillation and high-pressure membrane filtration.^{18,19} These systems depend on centralized infrastructure, which limits their adaptability to resource-limited settings.²⁰ Nanotechnology emerges as a frontier in clean water sustainability here by adding the nanoscale twist into these processes.^{1,21} For instance, a recent study on TiO₂@AlCl₃-Fumarate MOF highlighted its use to increase water vapor harvesting by 24.5% at low-pressure 0.2 P/P₀ at 25 °C.²² In addition, carbon nanotubes and graphene oxide nanoadsorbents have proven effective in removing a heavy metal (Pb²⁺) and antibiotics (ofloxacin, ciprofloxacin) from drinking water.²³ Nanozymes have further expanded the catalytic toolkit for targeted conversion of contaminants. Such progress points to a broader possibility – can nanotechnology become central to future water sustainability? I think the answer is yes, since nanotechnology not only reduces energy demand but also enables compact, modular systems. It can operate off-grid and in remote or resource-limited settings. Moreover, nanomaterials enable small-footprint, decentralized water solutions to be technically and economically feasible, making them well-suited for further upscaling.

From rags to riches

Beyond purification and desalination, a circular water future lies in closing the water-waste-resource loop by recovering nutrients and minerals. In agriculture, phosphorus and nitrogen flow from mines and ammonia plants through farms and cities into rivers and oceans. This linear path depletes finite phosphate rock and burdens energy-intensive fertilizer production. At the same time, it drives algal blooms, dead zones, and drinking water contamination.²⁴ Circular systems can reverse this pattern. Ion-exchange resins can capture ammonium and phosphate directly from wastewater and release them as valuable products such as ammonium sulfate and hydroxyapatite.^{25,26} Similarly, struvite precipitation transforms waste nutrients into magnesium ammonium phosphate crystals, with pilot systems achieving phosphate recovery efficiencies of up to 95%.²⁷ More advanced materials further expand this potential. Engineered adsorbents, such as layered double hydroxide composites combined with hydroxyapatite, can selectively bind both nitrogen and phosphorus and later release them for reuse, with the residual material serving as a soil amendment. Even desalination brine, traditionally treated as waste, can be reimagined as a mineral resource. Through electrochemical processes and multi-stage recovery systems, it can yield magnesium hydroxide, calcium carbonate, chlorine, hydrogen, and other valuable salts. These compounds are used as market-grade fertilizers and minerals, reducing dependence on mining and synthetic production while mitigating environmental pollution.²⁸⁻³⁰ In this way, what was once considered waste becomes a source of value.

The unfinished chemistry

Even with all the progress made so far, water remains chemically stubborn. The water we use daily is never just “water.” It is a shifting mixture of salts, organics, pathogens, heavy metals, pharmaceuticals, microplastics, and competing ions.³¹ These elements interact all at once, often in ways that are difficult to predict. This is where the next scientific frontier begins. The challenge is no longer just to remove contaminants, but to do so selectively, efficiently, and under messy real-world conditions. That will require a new generation of advanced materials. Membranes may need to separate nearly identical ions with biological precision. Catalysts may need to destroy one pollutant while leaving valuable nutrients untouched. Adsorbents may need to capture molecules present only in trace amounts, then release them on demand. Emerging tools such as biomimetic membranes, molecularly imprinted polymers, programmable sorbents, and AI-guided material discovery offer exciting possibilities. Still, many of these systems remain fragile outside the laboratory.³² Whether they can retain selectivity, stability, and performance in real wastewater remains one of the most important unanswered questions in the chemical sciences.

Science needs systems

But unfortunately, science alone does not move water systems: people, policies, and priorities do. Technologies such as plasma reactors may destroy PFAS, nanomaterials may harvest water from air or remove heavy metals, and wastewater may even return nutrients and minerals once treated as waste. Yet, none of these matters if

these technologies remain confined to papers, pilot plants, or elite laboratories. Real-life water systems are not neat, they are old, overloaded, and often unequal. Materials that work perfectly in the lab may fail in real wastewater. Costs rise, performance drops, and maintenance becomes difficult. Even the best technology means little if people cannot access it or do not trust it. Their translation will require coordinated regulation, sustained investment in treatment infrastructure, and equitable deployment.³³ Equally important is their ability to remain affordable, durable, and effective under the chemically complex and variable conditions of real water systems.³² Clean water is not only a scientific challenge, but it is also a human one. The future of water depends not just on what chemistry can invent, but on what society is willing and able to use.

Conclusions

The transition to a circular water future is no longer a distant goal, and it is within reach. Chemical sciences have already begun to redefine the story of water by eliminating persistent contaminants such as PFAS, enabling nanoscale purification, and transforming waste streams into sources of nutrients and minerals. What once seemed impossible is now technically feasible. Chemistry has, in many ways, fulfilled its promise of modern alchemy: turning the unwanted into the valuable, the toxic into the benign. Nonetheless, alchemy has never been just about transformation. It is about control, balance, and context. These technologies require clean and affordable energy to operate on a commercial level. There is a need for policies to support upscaling, markets that value recovered resources, and reliable infrastructure. Most importantly, the scientific innovations must function outside the laboratory, in real water conditions, under real constraints, for real people. Water has always connected everything, including ecosystems, economies, and communities, and therefore should not be treated as a disposable resource. Instead, it should be managed, recovered, and respected as a shared resource. The tools are now available, and the science is prepared, what remains is the collective will to bring it all together. If we succeed, clean water will no longer be part of the problem; it will become part of the solution.

Statement on use of AI

Grammarly was used in the preparation of this essay to improve the readability and language of this essay. All scientific content, interpretation, analysis, and conclusions were developed by the author. The author reviewed and revised the essay and accepts full responsibility for its contents.

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Finalist

From molecule to monitoring: analytical chemistry as the backbone of water security in the Global South

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Introduction

Millions of people rely on wells, rivers and informal networks of water for cooking, drinking and irrigation across the Global South.¹ Despite this, these water sources often carry unseen chemical threats. These include heavy metals, pharmaceutical residues from hospital and household, persistent pollutants such as per- and poly-fluoroalkyl substances (PFAS), pesticides from small holder farms and industrial wastes.² These contaminants contribute to antimicrobial resistance,³ undermine health, and have a disproportionate impact on underprivileged groups. As much as treatment technologies and filtration exist, contamination continues to persist, as a result of insufficient monitoring, detection and enforcement.⁴

Analytical chemistry is the missing infrastructure. The knowledge backbone of water governance is provided by chemical detection, which includes portable biosensors and high-resolution mass spectrometry.⁵ Without analytical chemistry, communities remain at risk, enforcement is reactive and standards remain symbolic. In low resource environments, there is a scarcity of skilled personnel, laboratories are concentrated in urban areas and regulatory capacity is constrained.⁶ Incorporating chemical sciences into governance allows for sustainable water access, public health protection and accountability by converting invisible pollutants to actionable evidence.

The evolving chemical threat landscape

Water contamination has shifted to complex chemical mixtures from classical microbiological threats.⁷ Despite PFAS being bioaccumulative, persistent and resistant to conventional treatment, they are widely used in consumer and industrial products.⁸ Pharmaceuticals such as analgesics, antibiotics and hormones enter water through run-off, improper disposal and wastewater promoting antimicrobial resistance.⁹ Industrial effluents introduce inorganic and organic pollutants while heavy metals and pesticides from mining and agriculture increase the risks further.¹⁰

The traditional monitoring techniques used in the Global South are inadequate. Outdated detection methods, sparse sampling and use of uncalibrated instruments mean emerging contaminants remain undetected and invisible.¹¹ Climate change makes the situation worse, drought concentrates the pollutants, floods mobilize chemicals from urban areas and soil, and infrastructure is disrupted by extreme events. Many communities hence face chronic exposure to these contaminants without recourse or knowledge.

To guarantee clean water, it is crucial to acknowledge this dynamic and ever-changing chemical landscape and develop monitoring systems that can detect both known and emerging threats. Without this chemical intelligence, it is impossible to achieve the United Nations Sustainable Development Goal 6 (SDG 6) which aims to provide everyone with access to safe and clean water.

Analytical Chemistry as Empowerment and Infrastructure

Analytical chemistry serves as both a social instrument and a technical tool. Colorimetric assays, portable sensors and biosensors provide real time decentralized monitoring while techniques such as gas chromatography- mass spectrometry (GC-MS) and liquid chromatography- tandem mass spectrometry (LC-MS/MS) detect trace contaminants.¹² Remote sensing enables predictive modelling at the watershed level by integrating chemical data with climate and hydrological information.¹³

Case study 1: A regional laboratory in southern Brazil monitored resistance genes and antimicrobial residues in sewage and drinking water. The obtained data supported municipal authorities to enforce actions and enabled citizen organizations to hold polluters responsible.¹⁴

Case Study 2: A university-led initiative in the Peruvian Amazon mapped antibiotic contamination in rivers using LC/MS/MS and biosensors. Data on water safety was made available to local communities, allowing them to advocate for municipal intervention, which in turn resulted in decreased pharmaceutical runoff and improved waste water treatment.^{7,15}

Technology is not enough on its own. Sustainable impact requires:

- Method validation and quality assurance to ensure accuracy.⁵
- Standardized protocols for reliable regionally comparable data.³
- Capacity- building and training to develop local technicians, chemists and community monitors.⁴

Analytical chemistry empowers governments and communities alike in low-resource settings. Science turns into governance when detection is transformed into actionable information.

Linking detection to accountability

For governance systems to be effective, detection must feed them. Communities, authorities and non-governmental organizations (NGOs) are able to identify sources, track contamination trends and implement corrective actions as a result of transparent, open-access water data platforms.⁴ The polluter-pays principle is supported by chemical fingerprints, which link pollutants to accountable parties.²

In rural or informal settlements, decentralized monitoring is somewhat effective. While local laboratories validate results, portable sensors offer early warnings.¹⁴ Harmonized chemical monitoring in transboundary basins can ensure that downstream populations are protected and prevent conflicts. Due to this, data becomes a feedback loop, converting molecular detection into enforcement, policy and public health outcomes.

Designing equitable and sustainable monitoring systems

In the Global South, social, technical and institutional integration is necessary for sustainable water security (Figure 1):

- Open-Access Platforms: According to UN-Water,⁴ researchers and the civil society can advocate for interventions, compare regions and visualize trends thanks to transparency.
- Regional Laboratory Networks: Inter-lab compatibility, standardization and efficiency are improved by shared infrastructure.⁵ It is important to understand that funding suitability are still very essential, regardless of whether training and equipment can be obtained through international partnerships
- Climate-Resilient Systems: Contaminant routes are affected by droughts, floods and agricultural practices. These changes must be anticipated by monitoring frameworks for them to remain effective.¹⁶
- Community Monitoring: The availability of inexpensive assays and portable sensors gives citizens the opportunity to identify pollutants and demand responsibility.¹⁴ Early warning systems enable exposure prevention and civic engagement.
- Capacity Building: Long-term sustainability is ensured by training local technicians and chemists instead of relying on outside experts, which builds local resilience.³
- Resource considerations- Investments in qualified staff, laboratory facilities, and community involvement are necessary for the creation and maintenance of these systems. Low-cost sensors and regional cooperation help overcome financial limitations.

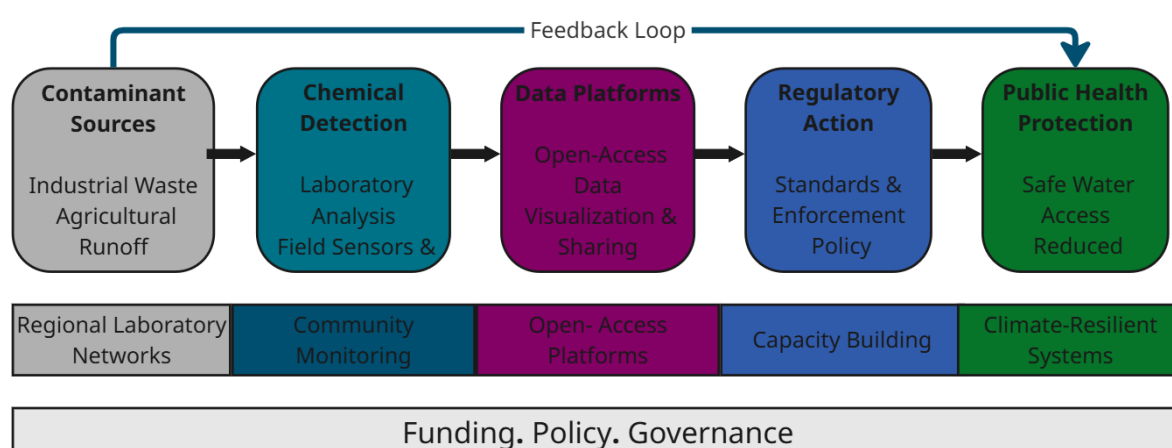


Figure 1 Integrated chemical monitoring and accountability framework for sustainable water access in the Global South

Towards a vision of water security in the global south

Inadequate infrastructure, excessive chemical exposure, vulnerable populations, and fragmented governance are some of the unique challenges that the Global South faces.¹⁷

Nonetheless, these areas offer opportunities for adaptability, innovation and systemic fixes. When chemical sciences are included into governance, monitoring turns into a locally owned development plan in which scientists, communities, and regulators collaborate as a cohesive network.⁴

International collaboration may expedite capacity building, finance laboratories, and give access to state-of-the-art analytical tools. Nevertheless, consistent funding, skilled personnel, and local ownership are critical for success. Institutions and individuals that depend on water for life, development, and livelihoods must continue to be responsible for monitoring, interpretation, and enforcement.¹⁴

Conclusions

Access to clean water is more about empowerment, accountability, and visibility than it is about treatment technology. Because monitoring is inefficient, contaminants persist. By converting unseen chemical hazards into actionable data that empowers communities, safeguards health, and informs policy, analytical chemistry fills this gap.^{2,3}

The Global South needs the following to achieve sustainable water security:

- Locally trained chemists,
- Robust laboratory networks,
- Climate resilient frameworks,
- Open-access data systems and,
- Decentralized monitoring tools.

From molecules to monitoring, chemical sciences offer knowledge, infrastructure and empowerment ensuring that safe water is a universally accessible right, and not a privilege.

Statement on use of AI

AI was used in the preparation of this essay to improve the grammar, spelling and clarity of the text after it was written. AI was not used for literature research, for generating scientific insights or conclusions, or for the primary writing of the essay.

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Finalist

A tandem MOF approach of NU-1000 and UiO-66 for PFAS capture and photocatalytic degradation

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Introduction

The history of per- and polyfluoroalkyl substances (PFAS) is a long one, spanning nearly a century. The first one, polychlorotrifluoroethylene, was first discovered by Fritz Schloffer and Otto Scherer at the German chemical conglomerate IG Farben in 1934. Just a few years later, in 1938, a young chemist at E. I. du Pont de Nemours and Company was experimenting with Freon gases, causing a new, earlier version of Teflon, tetrafluoroethylene resin, to accidentally be created.¹ Their ability to resist heat, water, and grease has caused them to become one of the most commercially used chemicals around the world, used in non-stick frying pans, floor polish, even skin creams! They are made up of an alkyl chain that is heavily saturated with fluorine. The carbon-fluorine bond, or C-F bond, is thermodynamic highly stable, making these chemicals virtually impossible to break down in the environment (**Figure 1**).^{2,3} This bond has a bond dissociation energy of about 485 kJ/mol, with the high electronegativity of the fluorine paired with the fact that it has a tiny radius, causing the carbon backbone to be heavily shielded, making it virtually impossible to break down through hydrolysis, advanced oxidation, or biodegradation.⁴

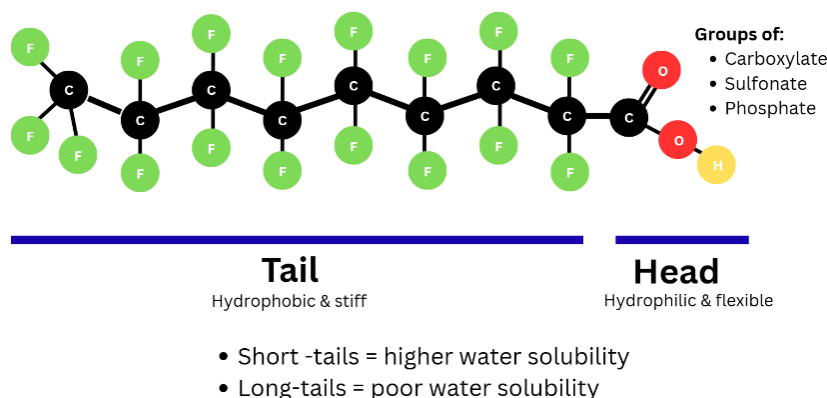


Figure 1 PFAS structure

The risk of PFAS for our global ecosystem

As a result of this widespread application of these compounds, PFAS has become ubiquitous in the global ecosystem and can be found in the soil, dust, food, and water supply of the world.⁵ In the rivers and lakes of England, for example, the threshold amount of PFAS in the local fish is defined at 77 ng/kg as a result of the widespread occurrence of this compound in the water supply.⁶ This widespread water contamination can be attributed to the amphiphilic properties of the molecule. The typical molecule of PFAS has a hydrophilic "head," meaning that the molecule has the tendency to attract water and draw itself into the water supply. On the other hand, the molecule has a long, nonpolar carbon-fluorine tail, which is strongly affinity to fats and oils. There has been a common misconception that if one were to touch the chemical, it would instantaneously poison the body, leading to death within a matter of minutes. This, of course, is not the case, but the true extent of the toxicity of the chemical is much more sinister. It is a chronic bio-accumulator, meaning that when we ingest even the smallest amount of it, the lipophilic tails allow it to quickly get into the bloodstream, where it will embed itself deep into the fatty tissues of vital organs such as the heart, brain, and lungs.⁷ This has been known to lead

to the degeneration of the immune system, severe disruption of the body's hormones, and even reproductive abnormalities.⁸

MOFs against PFAS

To tackle this PFAS problem, we need nanoscale tools, called Metal-Organic Frameworks (MOFs). This is a field of chemistry that is extremely cutting-edge. Just recently, in October 2025, Susumu Kitagawa, Richard Robson, and Omar Yaghi received the Nobel Prize in Chemistry for their pioneering work in this field.⁹ MOFs are crystalline materials that contain metal nodes and organic carbon-based bridges. They are also very well known throughout the scientific community due to their extremely high porosity, such as that of MOF-5, which has a surface area of 2200 m²/g.¹⁰ At the moment, chemists are already developing and using MOFs to combat PFAS in two ways (**Table 1**):^{11,12}

Table 1 MOF-based strategies for PFAS capture and degradation

High-Affinity Adsorption of PFAS	Degradation of PFAS via Light
Designing of MOFs that contain zirconium nodes, which are perfect chemical sponges. The extremely positive zirconium nodes can form extremely strong electrostatic bonds with the negatively charged PFAS headgroup.	Utilizing light-activated MOFs, such as UiO-66 or PCN-222. When these MOFs are exposed to intense UV or visible light, they release electrons that behave like molecular scissors to snip extremely strong C-F bonds.

A thought experiment: capturing, concentrating, and degrading PFAS

However, simply adsorbing PFAS in water is not sufficient. To obtain PFAS-free water, we need to degrade PFAS. This thought experiment will follow a two-step process to adsorb PFAS and then degrade them by targeting the strong C-F bonds. This can be achieved by a multicomponent MOF system with NU-1000 and UiO-66 (**Figure 2**).¹³ In detail, NU-1000 is a Zr-based MOF with Zr₆O₈ clusters connected by large pyrene linkers to form a hexagonal structure with one-dimensional pore sizes of ~30-35 Å and a high surface area of 2000-2400 m²/g.¹⁴ It is highly stable in water over a pH range of 1-10 and can efficiently concentrate PFAS due to the fast diffusion of PFAS into the large channels of NU-1000.¹⁵ UiO-66 is another Zr-based MOF with Zr₆O₄(OH)₄ clusters connected by terephthalate linkers. UiO-66 is very tightly microporous with pore sizes of 6-8 Å and a surface area of 900-1500 m²/g.¹⁶ It has a band gap of ~3.8 eV to absorb mostly UV light to drive the photocatalytic reaction.¹⁷ In order to achieve this synergy, the pores of the NU-1000 must remain open, the UiO-66 must adsorb onto the surface of the NU-1000 without blocking the pores, and the charge generated at the UiO-66 must be efficiently transferred to the PFAS molecules. This can be achieved by growing the UiO-66 onto the surface of the NU-1000 in a controlled environment. The Zr-OH groups on the surface of the NU-1000 act as the nucleation sites for the UiO-66 nanoparticles, which are only a few nanometers in size. The adsorbed PFAS molecules are then in close proximity to the catalytic sites on the UiO-66 surface, which are essential for the photocatalytic degradation of the PFAS molecules.¹⁸

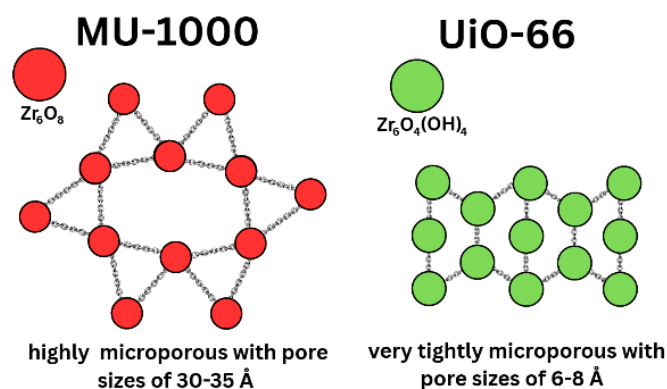


Figure 2 Structural illustration of NU-1000 and UiO-66

This can be achieved in three phases:

1. *Capture*: The PFAS molecules are captured by the NU-1000 and adsorb onto the Zr–OH groups.
2. *Cleavage*: Light is shone onto the UiO-66 surface, which generates radicals that cleave the C–F bonds.
3. *Mineralisation*: The PFAS molecules are then further degraded into F[−] ions, CO₂, and other small molecules, which then react with the calcium ions to form CaF₂.¹⁹

This demonstrates the potential of using the adsorption and photocatalytic degradation of PFAS using the MOF system for a clean water approach. However, certain limitations are associated with the NU-1000 + UiO-66 system, such as the slow degradation rate of PFAS because of the presence of strong bonds between C and F, as well as incomplete mineralisation and the production of short-chain fragments. It is also important to say that for effective photocatalysis, enough UV or visible light must be available. Additionally, diffusion can be restricted if UiO-66 fills the pores of NU-1000, while stability can be affected by pH or other ions. It might also be difficult and expensive to upscale a well-controlled synthesis of the tandem MOF composite.

Conclusions

PFAS are highly resistant pollutants that are hard to degrade. This tandem MOF system, which employs the combination of NU-1000 and UiO-66, can be an effective method of addressing the problem of PFAS contamination in water. The NU-1000 MOF has large pores that are effective in capturing the PFAS, while the UiO-66 MOF has the ability, under light, to degrade the C–F bonds of the PFAS. Further studies are welcome.

Statement on use of AI

I have used AI for language editing only, and sometimes to provide me with some chemical knowledge and know-how. After utilizing this tool/service, I have reviewed and edited the content as required, taking full responsibility for the publication.

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Finalist

Water, water, everywhere, nor any drop to drink: can chemical sciences provide the missing link?

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"Water, water, everywhere, / Nor any drop to drink." We have all heard this poem by Samuel Taylor Coleridge during childhood. While originally referring to a sailor's plight in the vastness of the ocean, this reality has now reached those of us on land. Freshwater comprises merely 2.5% of all water on Earth, and within this limited freshwater, rivers, lakes, and wetlands account for less than 0.01%. Yet they are the primary source of water because of their ease of accessibility.¹ Adding to this scarcity is the contamination of freshwater sources. The United Nations recognises that access to clean water is a basic human right, crucial for life, dignity, and health. However, 2.2 billion people, nearly 29% of the world's population, still lack access to safe drinking water, with pathogens and toxins in contaminated water causing over two million deaths annually, predominantly among children under five.²

The age of Artificial Intelligence (AI) adds a new layer to this crisis. AI can help with real-time monitoring of water, predicting contamination levels and treatment outcomes. Ironically, the same AI needs huge amounts of clean water for its cooling systems.³ Every technology has its pros and cons; what separates it from a harmful technology is how mindfully we use it. To ensure this age of development is sustainable for future generations, we must look at where the actual crisis begins: the deteriorating chemistry of our freshwater. This understanding is the missing link between a scarce present and a future with clean, accessible water for all.

The decline in water quality is most evident in the condition of our river systems today. Growing up in India, where rivers are traditionally considered sacred, their importance is both spiritual and physical. The whole Indo-Gangetic plain sustains the civilisation that has developed around it, yet it is also burdened by pollutants from anthropogenic activities. Studies along the Ganga show water quality indices (WQIs) ranging from 28.27 to 66.98, revealing significantly compromised water quality at key monitoring sites.⁴ The fertile land supports agriculture, but pesticides ultimately leach into groundwater, making it unfit for consumption.⁵ Industrial waste and untreated sewage have increased ammonia and other chemical levels, creating hotspots for microbial growth and raising biochemical oxygen demand (BOD).⁶ This deteriorates aquatic ecosystems and threatens human health. Concentrations of carcinogenic heavy metals, including lead, mercury, and cadmium, have consequently risen in rivers.⁴ Globally, arsenic affects approximately 230 million people, with studies documenting elevated cancer risks from contaminated drinking water exposure.⁷ Identifying the problem is just the first step; the next step is to evaluate and measure the amounts of pollutants with the help of chemical science.

Spectroscopic methods like atomic absorption spectroscopy (AAS) detect arsenic or lead by vaporising samples and measuring the characteristic wavelengths of light absorbed by ground-state atoms. While AAS is accessible and widely deployed, inductively coupled plasma mass spectrometry (ICP-MS) offers greater sensitivity by ionising samples in a plasma and detecting trace elements at lower concentrations, such as parts-per-trillion (ppt).⁷ Nanoparticle-based electrochemical sensors, such as those based on gold nanoparticles, graphene, and carbon nanotubes, are increasingly used for detecting freshwater pollution. The high surface-area-to-volume ratio of these nanomaterials facilitates faster electron transfer during anodic stripping voltammetry for heavy metal detection.⁸ Metal oxide-based electrochemical sensors, like zinc oxide and indium oxide heterostructures, are being used for detecting contamination due to pesticide assimilation in groundwater.⁵ Internet of Things (IoT) integrated monitoring systems, enhanced by deep learning neural networks, can continuously track water quality and automatically alert authorities when contamination exceeds safe thresholds.⁹ This principle has been deployed on the Ganga, where a Supervisory Control and Data Acquisition-based network of IoT-connected sensors simultaneously monitors 17 parameters, including BOD, dissolved oxygen, nitrate, and pH across multiple stations.¹⁰

Contaminated groundwater also harbours antibiotic-resistant bacteria, a problem further compounded by the rise of pharmaceutical pollution in our waterways.¹¹ Though the world has moved on from the COVID-19 pandemic, its effects still linger. The surge in antibiotic use has come at a hidden cost to freshwater quality. Even at concentrations too low to kill microbes, antibiotics can drive resistance, making infections increasingly difficult to treat.^{11,12} A further failure of green chemistry principles lies in the pharmaceutical industry's untreated

disposal of waste from drug manufacturing and hospitals into freshwater.¹³ These wastes, along with micro- and nanoplastics and per- and polyfluoroalkyl substances (PFAS), are classified as emerging pollutants due to their persistence and resistance to conventional treatment.¹⁴ The stability of PFAS comes from the strong carbon-fluorine (C-F) bond; fluorine's high electronegativity and significant orbital overlap make it difficult for natural microorganisms to break down.¹⁵ Micro- and nanoplastics have non-polar, hydrophobic surfaces which act as chemical sponges, concentrating heavy metals through electrostatic interactions and persistent organic pollutants through van der Waals forces from surrounding water.¹⁶ Techniques like differential pulse voltammetry apply small voltage pulses to water samples, which helps filter out background electrical noise. This means it can measure the unique signal of each contaminant simultaneously, even at trace concentrations.¹⁷ While detecting these pollutants is only the beginning, the greater challenge lies in their removal.

Different contaminants require different chemical solutions. Reverse osmosis forces contaminated water through a semipermeable membrane, driving it from a region of high solute concentration to a lower one and leaving contaminants like dissolved salts, heavy metals, and pathogens behind by size and charge exclusion.¹⁸ Electrocoagulation passes electric current through water via metal electrodes, releasing metal ions that act as *in situ* coagulants, neutralising and removing heavy metals and suspended solids without chemical additives.¹⁹ Chemical coagulation-flocculation achieves similar results by adding coagulants like ferric chloride (FeCl₃) to neutralise suspended particles, causing them to aggregate into flocs that settle through sedimentation. This method was successfully optimised for river water treatment at a turbidity level of 677.78 nephelometric turbidity units (NTU).²⁰ Organic pollutants can be broken down through bioremediation, where microorganisms use enzyme-catalysed redox reactions to metabolise contaminants as carbon sources. In aerobic conditions, enzymes like monooxygenases break down complex hydrocarbons, which can ultimately be mineralised to CO₂ and H₂O.^{21,22} Effective microorganisms successfully rejuvenate polluted rivers through this principle.²³ Emerging pollutants like PFAS and microplastics are degraded by advanced oxidation processes (AOPs). AOPs generate highly reactive hydroxyl radicals (•OH) that break down complex aromatic rings in the pollutants to CO₂ and H₂O. In Fenton processes, iron ions react with hydrogen peroxide (H₂O₂) to produce these radicals, while UV/TiO₂ photocatalysis degrades pollutants under UV or sunlight, offering a cost-effective solution for resource-limited regions.²⁴ Nanocomposites, such as graphene oxide-based materials, remove organic dyes from industrial wastewater through surface adsorption and subsequent chemical degradation.²⁵ But cleaning water means nothing if we keep polluting it.

Remediation without prevention is like treating a disease while remaining exposed to it. Green chemistry principles demand eradicating pollution at the source. Stricter regulations must mandate wastewater treatment, require industries to locate away from water bodies, and ensure technologies account for their environmental impact before deployment.²⁶ Where penalties do not work, incentives might! For example, providing subsidies for safer alternatives to pesticides to farmers, or incentives for rainwater harvesting to households, or subsidies for green infrastructure solutions to industries.²⁷ This would encourage people to participate in keeping water bodies clean and safe at the community level. AI data centres require large amounts of clean water, but this is not unavoidable. Methods like recycling water for cooling, such as closed-loop systems implemented by NTT Global Data Centres, allow water to be continuously reused and purified, significantly reducing consumption.²⁸ At the same time, AI and IoT networks can scale water monitoring systems globally, making real-time surveillance accessible even in remote regions.⁹ Initiatives like people-friendly water quality test kits developed specifically for the Ganga demonstrate that chemistry can serve both accessibility and accuracy, not just precision in laboratories.²⁹ Providing safe water also reduces the economic burden by lowering healthcare costs.³⁰ However, first and foremost, water must be recognised as a fundamental right in order to make it accessible and essential for all.

Chemical science has given us the tools to detect contamination, remediate polluted sources, and prevent further damage. Green chemistry principles, from designing safer chemicals to treating wastewater before discharge and adopting reduce, reuse, and recycle, shift our focus from treating pollution to preventing it.^{26,31} However, tools alone are not sufficient. Science doesn't work in isolation; sustainable water access demands participation from scientists, industries, policymakers, and citizens alike. In doing so, we move closer to achieving Sustainable Development Goal (SDG) 6, safe and clean water for all by 2030.³² The missing link between a deprived present and a sustainable future is not chemistry alone, but chemistry made accessible to all. Coleridge's sailor couldn't drink the water around him, but we can by purifying the sources we made dirty and protecting the sources we still have.

Statement on use of AI

AI was used in the preparation of this essay for grammar correction and improving the clarity of text written by the author. These tools were not used for initial text drafting, scientific idea generation, data analysis, or drawing

conclusions. All AI-assisted suggestions were thoroughly reviewed, edited, and finalised by the author to ensure accuracy and original content.

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Finalist

***Soft solutions to a hard problem:
chemistry's role in universal water access***

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Introduction

More people lack access to clean water today than the entire population of the American Continent. As of 2025, according to *The Sustainable Development Goals Report 2025*, billions of people still lack access to essential Water, Sanitation, and Hygiene (WASH) services.¹ In 2024, an estimated 2.2 billion people lacked safely managed drinking water, 3.4 billion people lacked safely managed sanitation, and 1.7 billion people lacked basic hygiene facilities at home.² The *United Nations World Water Assessment Programme* also noted that whilst Nature-Based Solutions often offer cheaper, cost-effective alternatives to grey infrastructure, they receive less than 1% of water management investment in water projects globally.³ The 2024 United Nations (UN) Water update highlighted a global gap in sanitation, reporting that at least 113 billion cubic meters of untreated water enter the environment annually. To solve these challenges, the report called for a transition toward water infrastructure modelled as a circular economy.⁴ This means rethinking water infrastructure, treating wastewater as a resource rather than a burden.

In the Global South, many cities are faced with a dire water and sanitation crisis. Across Africa, the urban population without sanitation services increased from 88 million in 1990 to 175 million in 2008. In East Africa, the scale of the infrastructure gap is evident in cities such as Addis Ababa, where less than 3% of wastewater reaches treatment facilities, while in Kampala, the Bugolobi Sewage Treatment Works covers only 55% of the sewage produced within the Nakivubo catchment area, with the remainder discharged into surrounding natural wetlands without treatment.⁵ This is arguably one of the major threats to public health across most of sub-Saharan Africa. For the millions of people living in the Sahel or young students in low-income settlements in Kisumu or Dodoma, these statistics aren't just numbers on a sheet; they represent barriers to dignity and health.

Addressing this crisis through centralized infrastructure alone is, at this moment in time, not financially feasible and sustainable. New centralized water systems would cost billions of dollars to implement and manage. To quickly connect the entirety of the continent on new water infrastructure would need governments to implement mega projects financed through expensive debt, which would be counterproductive to their economies.

The chemical sciences offer an innovative alternative. The field of soft matter materials promises great ability to innovate in water remediation systems and quality monitoring. Among the soft matter systems, hydrogels and various biomaterials have emerged as highly promising platforms due to their tuneable structures, biocompatibility, and responsiveness to environmental stimuli. These materials can enable a fundamental shift in how water systems are designed and managed.

Water remediation using hydrogels

One of the most promising directions in hydrogel research is the shift toward bio-based designs. Researchers have been able to use natural polymers such as cellulose, chitin, and guar gum to develop hydrogels with 3D porous networks capable of removing a wide range of contaminants, including heavy metals, microplastics, pharmaceuticals, and industrial dyes.⁶⁻⁹ As illustrated in **Figure 1**, these materials combine selectivity, tuneable surface chemistry, and mechanical adaptability, making them excellent for next-generation water treatment technologies. Importantly, many of these biopolymers can be derived from agricultural and seafood waste available across sub-Saharan Africa, enabling affordable local production.

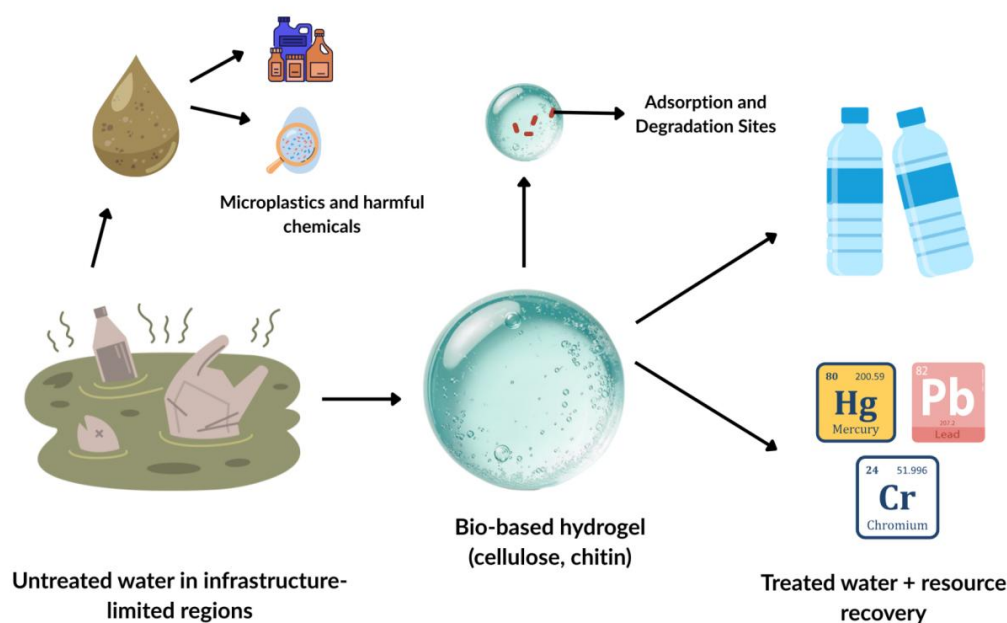


Figure 1 Soft matter-based water remediation and resource recovery system. Bio-based hydrogels functionalized with selective binding sites remove contaminants, including heavy metals, pharmaceuticals, microplastics, and dyes, through adsorption and catalytic degradation. Captured pollutants may subsequently be recovered or transformed into valuable products, supporting circular economy principles for sustainable water treatment.

The increasing chemical complexity of modern water pollution can be effectively tackled by deploying hydrogel-based filters. Nature-derived hydrogels composed of chitin and modified lignin can selectively capture nanoplastics through electrostatic interactions, achieving adsorption capacities far exceeding those of conventional materials.⁷ Similarly, hybrid systems incorporating bacterial cellulose and amine-rich polymers have demonstrated high removal efficiencies for antibiotics such as tetracycline and metronidazole.⁸

One of the most promising applications of hydrogels lies in the capture and recovery of heavy metals. Gels based on materials such as carboxymethyl cellulose and polyacrylamide have demonstrated strong affinities for toxic ions like lead and cadmium.⁶ Apart from adsorption, these systems can support circular economy approaches, where captured metal ions are reduced into functional nanoparticles within the hydrogel matrix, enabling the material to be reused as a catalyst in other processes.

Recent advances have also expanded the role of hydrogels into active pollutant degradation. By embedding catalytic components such as enzymes within the polymer network, researchers have created systems capable of breaking down persistent organic pollutants directly within the material.¹⁰ These kinds of systems can enable a reduction in the reliance on multi-stage treatment processes.

Overcoming industrial limitations such as slow adsorption kinetics can also be achieved. By utilizing zwitterionic backbones, researchers at Massachusetts Institute of Technology (MIT) increased the internal mesh size of the hydrogels while providing counterion-free adsorption sites. This addresses the limitation of slow uptake due to chemical diversity and low pollutant concentrations, which is common in industrial adsorbents. Consequently, the hydrogels performed at least 10 times faster than commercially activated carbon-ion exchange resin mixtures and up to two orders of magnitude times faster than other existing multifunctional adsorbents.¹¹ With the recent advancements in hydrogel research, new water treatment systems can be developed and scaled to make access to water easier across the world.

Stimuli-Responsive Hydrogels for Water Quality Monitoring

Stimuli-responsive hydrogels can improve how we implement water quality monitoring by enabling the development of portable sensing infrastructure. Hydrogels can be functionalized with molecular recognition elements that convert environmental changes into detectable optical or electrical signals, making them suitable for on-site water quality assessment.

Figure 2 provides a conceptual overview of how functionalized hydrogels translate environmental stimuli into measurable sensing signals. Photonic and luminescent hydrogels offer visually observable responses to contaminants. Researchers have developed enzyme-functionalized hydrogels that can detect pharmaceutical residues such as penicillin through pH-triggered color changes, enabling intuitive, user-friendly sensing. Similarly, lanthanide-based systems enabled fluorescence-based detection of metal ions, such as copper, while simultaneously responding to environmental parameters, including temperature.^{12, 13}

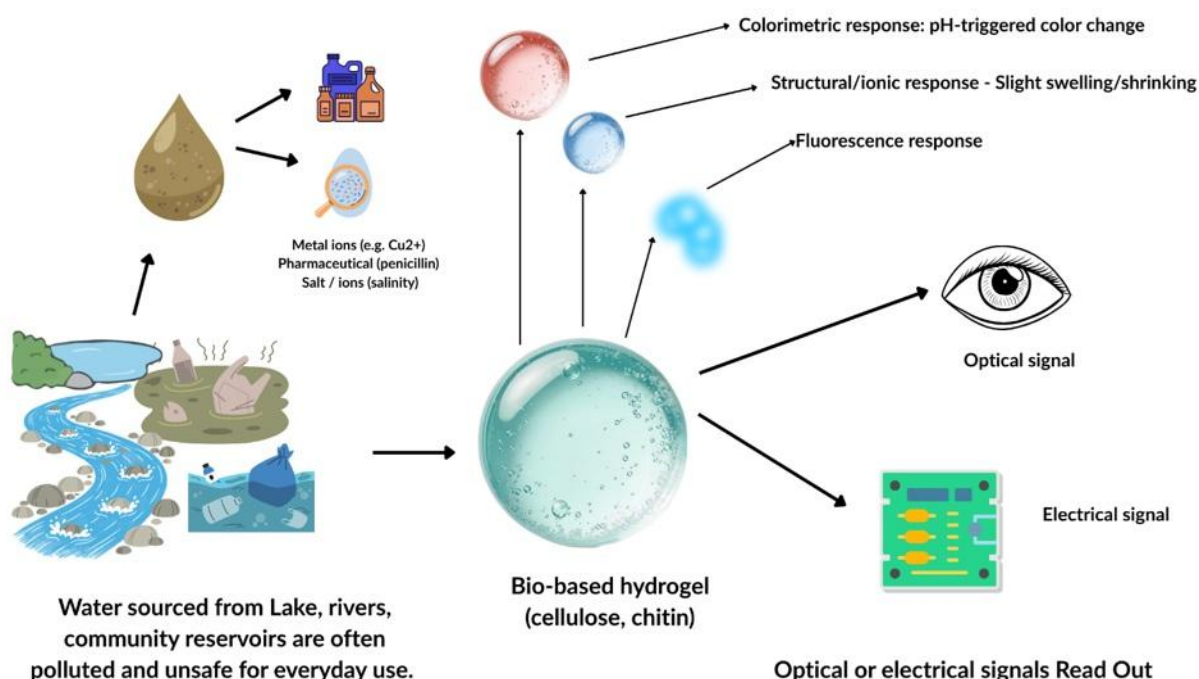


Figure 2 Mechanisms of stimuli-responsive bio-based hydrogels for water quality monitoring. Functionalized hydrogels respond to chemical or physical stimuli by producing optical, fluorescent, or electrical signals, enabling rapid on-site detection of contaminants and real-time assessment of water quality without centralized laboratory infrastructure

It is also possible to utilize physicochemical effects, such as the Hofmeister effect. The working principle is that the hydrogel will swell or shrink in response to the concentration of seawater ions, acting as a structural "switch" that converts salinity levels into measurable signals. Thus, enabling the monitoring of salinity in marine systems.¹⁴

Real-world Deployment Initiatives

Researchers at Universitat Politècnica de Catalunya (UPC), through the TherGel project, are developing high-performance solar absorber hydrogels (SAHs) to enhance water access. By integrating poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), a conducting polymer into a poly(N-isopropylacrylamide) (PNIPAAm) matrix, researchers discovered the "pudding effect". This is a solar-driven structural shrinkage process that concentrates heat and accelerates water transport. Enhanced with an alginate scaffold, the soft matter gels achieved a peak evaporation rate of $4.50 \text{ kg m}^{-2} \text{ h}^{-1}$ and a solar thermal efficiency of 197%. These robust gels effectively desalinate seawater using only natural sunlight, offering an affordable solution for decentralized domestic water remediation.¹⁵

Policy and societal implications

Governments across the Global South should fast-track the implementation of laws that accelerate the approval and funding for decentralized water technologies, with priority given to rural and semi-urban settlements that are poorly served by conventional infrastructure.

The real test for researchers will be to deploy these systems on the ground in peri-urban and rural settlements, running pilots and building the evidence base that attracts real investment. Young innovators could also leverage locally available bio-based materials like chitin and co-develop these technologies. Funding for the new technology could come from public-private partnerships that could also establish local manufacturing ecosystems across the continent. **Figure 3** summarizes the idea of a hybrid water infrastructure model that integrates centralized utilities with decentralized soft matter technologies through collaboration between researchers, policymakers, industry, and local innovators.

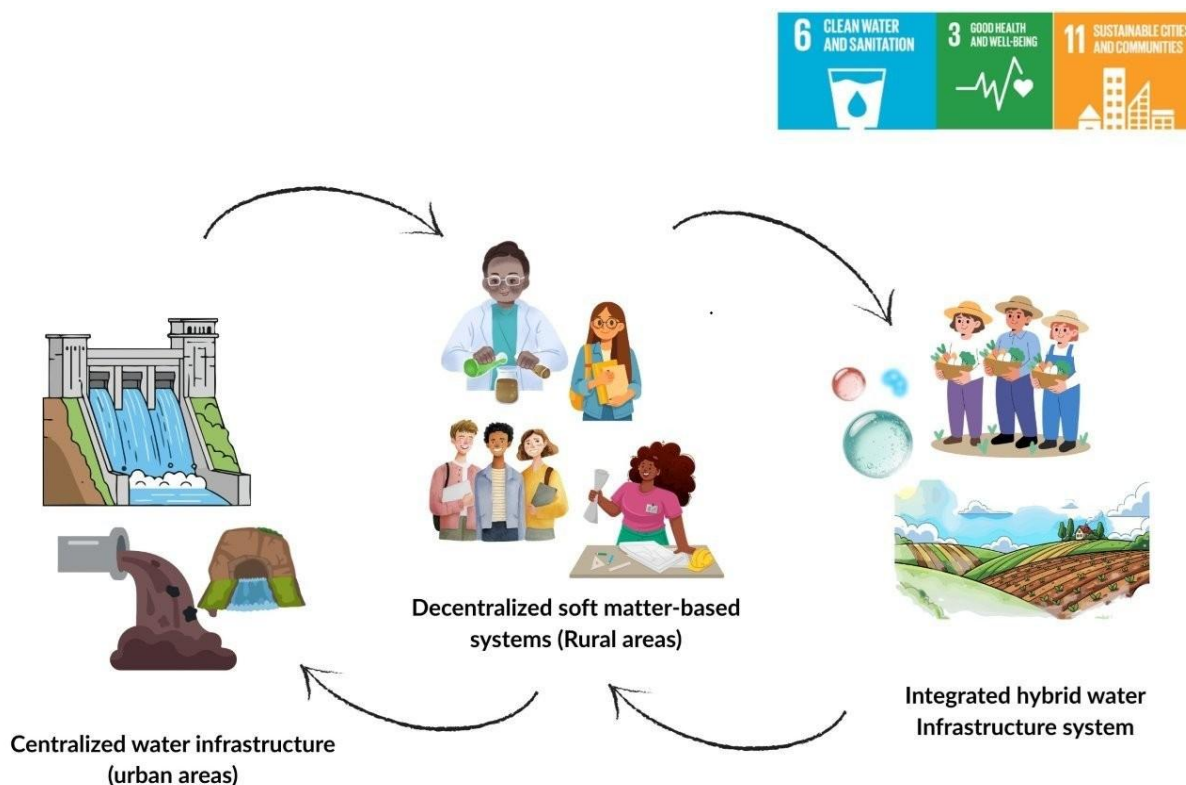


Figure 3 Integrated hybrid water infrastructure system. This model depicts the synergy between centralized urban utilities and decentralized soft-matter innovations, fueled by collaborative innovation and input from innovators, policymakers, and scientists.

The most viable path forward may be hybrid systems, centralized infrastructure serving dense urban centers, complemented by intelligent soft matter-based solutions deployed in remote and hard-to-reach communities.

Conclusions

The chemical sciences can enable sustainable access to clean water for all needs. Engineered soft matter can develop water systems that clean, monitor, and recover resources with the principles of the circular economy. Soft matter materials have the potential to enable new decentralized water systems that can sense and remediate contamination.

The water infrastructure gap that exists in places like sub-Saharan Africa provides a vacuum that can be utilized to position the continent as a testing and innovation hub for portable intelligent, soft-matter-based purification systems. Much of the continent runs on agriculture, meaning innovators can utilize locally available agricultural waste to make the purification and sensing hydrogels.

Structural durability, scalability, and real-world integration are the most challenging problems in deploying soft matter systems and will require sustained collaboration between researchers, industry, and local communities to overcome. As these barriers are addressed, soft matter chemistry stands to play a defining role in ensuring that clean water is accessible to all.

Statement on use of Artificial intelligence (AI)

Artificial intelligence (AI – Google's Gemini) was used in the preparation of this essay to improve the language and readability of the manuscript; it was not involved in data analysis, interpretation, or the production of scientific insight.

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Finalist

Redemption arc: forget microplastics, could polymers actually hold the key to water purification?

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Introduction

Water is humanity's most fundamental need, essential for drinking, agriculture and industry. Yet despite water covering 71% of Earth, just 3% is fresh, of which only 1% is drinkable.¹ Sustainable water access for all requires close guarding of scarce resources. Unfortunately, clean water is under threat from physical, biological, chemical and radiological pollutants. Intensive agriculture and rapid industrialisation have degraded the quality of our water, which bodes significant consequences for the environment and for humanity.¹

A wide range of strategies exist for cleaning up water supplies and providing potable water, but we face two main challenges. Firstly, continuous evolution of purification technologies is required to ensure that new threats to water supply, such as microplastics and "forever chemicals", can be contained.²⁻⁴ Secondly, to ensure an equitable share of water resources, new innovations must be scalable and cost effective.

Existing primary routes of purification include flocculation, ion-exchange, biological disinfection and adsorption, each playing a differing vital role in restoring water quality.³ This essay will focus upon advances in polymer-based adsorption technologies, as this is an area where chemistry can make the greatest gains with regards to ensuring clean, abundant and equitable water supplies. Coagulation and flocculation technologies, and biological decontamination techniques, such as ultraviolet sterilisation or chlorination, are already highly efficient, scalable and cheap.^{3, 4} By contrast, adsorption technologies are less developed commercially and so there remains greater space for development. In this work, polymer technologies for the removal of heavy metal ions and pharmaceuticals are discussed.

With regard to water cleanliness, polymers are often maligned as they are the origin of microplastics, an emerging pollutant of increasing significance. However, appropriately designed and used, polymers are also a valuable tool for water purification. Polymer chemistry is particularly useful for the development of new adsorption platforms as polymers can be carefully engineered for different tasks by modulating their chemical and physical properties. By modifying chemical structure, surface chemistry and structural forms, polymer chemists can design new materials with many benefits, from highly-selective adsorption, to high mechanical strength and degradation resistance.

Heavy metal ions

A core element of industrial pollution, heavy metal ions are a major issue for water purity, as they are highly harmful to humans and other species. Adsorption could offer a scalable and cost-effective solution to dissolved metal ions, and yet currently deployed technologies remain inefficient.² Fortunately, a number of polymers have been developed that show high-efficiency adsorption capabilities and could supplant existing technologies.

In particular, chitosan has proven adsorption capabilities and could be produced sustainably at scale, as it is derived from chitin, found in crustacean shells, a waste product of the seafood industry, and highly abundant in mushroom cell walls. Chitosan has an intrinsically high affinity for metal ion adsorption owing to numerous amine and hydroxyl groups in its structure; further modifications can maximise the effectiveness of adsorption. Grafting chitosan to melamine via glutaraldehyde has been shown to increase its affinity for lead and mercury ions, and the modified polymer can be regenerated for reuse.⁵ Combined polymer networks based on chitosan have also shown success, with an interwoven network of chitosan and 2-hydroxymethacrylate showing high affinity for copper, zinc and calcium ions.⁶

Cellulose, another highly abundant polysaccharide, has similar promise, with copolymers of cellulose, N-isopropylacrylamide and acrylic acid showing efficient adsorption of nickel, copper and lead ions.⁷ The copolymer significantly outperforms the unmodified cellulose, showing the role that chemical modification can play. Other works have shown cellulose derived polymers as capable of adsorbing an expanded range of metal ions.^{7, 8} Importantly, cellulose can also be derived from waste products like rice husks, so can also be deployed sustainably and renewably.⁹

Research on stimuli responsive polymers is particularly useful to allow for selective desorption of ions and reuse of adsorbents. Recent developments include synthesis of a copolymer system based on acrylamide and 2-acrylamido-2-methylpropane sulfonic acid that selectively adsorbs copper, cadmium and lead ions at neutral pH, with release under acidified conditions.¹⁰ Polymerisation of acrylamide and acrylate polymers is particularly useful, as it tolerates diverse monomer structures and ratios, allowing for easy synthesis of custom copolymers, which can be tailored to specific properties and behaviours.¹¹

Alternative work has instead exploited temperature responsive polymers for adsorption/desorption, including the development of a poly(*N*-isopropylacrylamide) hydrogel incorporating benzo-18-crown-6-acrylamide. The 18-crown-6 motif is a potent lead ion acceptor, but at elevated temperatures, the hydrogel network shrinks, and lead ions are released.¹² Similar effects have been achieved in a related hydrogel network that instead uses acrylic acid as a copper adsorbent.¹³ Meanwhile, other work has exploited stimuli such as light and magnetism for selective ion adsorption.^{14, 15}

A key threat to clean water supplies, heavy metals can be efficiently targeted by many polymers. Unfortunately, many complex polymers are costly and polluting to produce at scale. When seeking sustainable solutions, researchers must not just to develop the highly efficient materials we need, but consider the impacts of the full lifecycle of development, production and application. For this reason, bioderived polymers provide a particularly promising platform.

Pharmaceutical pollution

The complexity and variety of organic chemical pollutants in water can make treatment complex and expensive. Pharmaceutical molecules, including antibiotics and endocrine disrupting agents, are a key component of pollution, impacting both humans and ecosystems. Additionally, pharmaceuticals can act as a proxy for other organic pollutants such as pesticides and dyes, and so adsorbents tested for the purpose of removing pharmaceuticals may also be useful for removing other pollutants.

To remove a wide range of compounds, each with unique structures, adsorbents should target common functional groups; porous aromatic frameworks show promise for this.¹⁶ Commonly formed by the polymerisation of aromatic monomers, these frameworks are effective for removing many aromatic compounds owing to strong pi-pi (π - π) attraction between the polymers and contaminants. Further, the porous nature of the framework offers a large surface area for high adsorption efficiency, and tuning the structure of the polymer and the network can be used to modulate pore size for targeting of specific contaminants.¹⁷ Researchers have found them to be efficient at adsorbing a range of pharmaceuticals and other organic contaminants like dyes.^{2, 18} π - π interactions have also been exploited in other materials, with a number of polystyrene derivatives synthesised and tested for adsorption of a number of aromatic compounds. Polystyrene derivatives are cheap, ubiquitous and stable, showing good potential for scalability.^{19, 20}

Adsorption into pores is also the aim for polymers of intrinsic microporosity (PIMs), materials that can adsorb a wide range of contaminants. The rigid structure of the constituent polymers results in a highly porous network, with specific pore structures and chemical identities tuneable by altering the constituent monomers. Through tailoring the polymer properties, PIMs have been adapted for adsorbing a wide range of organic chemicals, with some early work demonstrating a capability to adsorb both cationic and anionic dyes at the same time.²¹ Subsequent work has exploited their high surface area and synthetic versatility to target many pharmaceutical contaminants and other organic molecules.^{22, 23} Similarly, a number of highly cross-linked polymers have been developed to form highly porous networks, which act in an analogous manner.^{24, 25}

Many polymers have also been developed that utilise different mechanisms to optimise adsorption. This includes copolymers of acrylic acid and 1-vinylimidazole, which exploit the complementary acid/base nature of the monomers to maximise hydrophilicity to adsorb anti-inflammatories.²⁶ Other researchers developed amine rich copolymers of polyaniline and polypyrrole to adsorb pollutants with high nucleophilicity like metronidazole. Adsorption is driven via hydrogen bond formation, introducing a different mechanism to porosity driven adsorption and π - π stacking detailed previously.²⁷

The identities of pharmaceuticals and other organic pollutants in our water are ever changing depending on current usage. Therefore, alongside the development and adoption of effective adsorbents targeting current pollutants, we require a continuous analysis of new pollutants to ensure adsorbents remain fit for purpose.

Conclusions

Equitable access to clean water requires purification technologies to be reliable, affordable and scalable. Beyond this, polymer adsorbents must demonstrate resistance to degradation over time; high-efficiency adsorbents are no use if they contribute to water pollution themselves. Chemistry continues to offer new innovations for purification that can progress humanity towards the goal of water for all. However, new developments in

isolation are insufficient to solve the issues of water accessibility. Not only must the funding landscape continue support new research projects, but we require national and international political will to develop new purification strategies alongside industrial demand to support their adoption.

It is incumbent upon researchers to engage with policy makers and the public to share their research and make the case for additional research funding and a policy environment that incentivises adoption of new technologies. Additionally, governments must limit water pollution at the source, rather than relying on new technologies to relieve this burden; prevention will always be cheaper and easier than remediation.

Global, equitable access to clean water is a difficult goal, but not unobtainable. Although there are many economic, political and social factors at play, chemistry remains a key player in developing the new technologies that will make this possible.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

***Clean water for all needs:
harnessing agricultural wastes for sustainable access***

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Introduction

Water covers nearly three-quarters of the Earth's surface, yet 2.2 billion people cannot access a safe glass of clean water, 400 million of them in Africa alone.¹ For drinking and sanitation, agricultural irrigation, industrial processing, and aquatic ecosystems, clean water is at the centre of every human and ecological need, its contamination is therefore one of the defining chemical crises of our time. Contaminants like synthetic dyes from textile industries, pharmaceutical residues, and microplastics are commonly detected in water bodies across the developing world, rendering them unsuitable for domestic and industrial uses.^{2,3} Chemical scientists, through their capacity to design materials, engineer reactions, and tailor solutions to specific contaminants, are uniquely positioned to address these challenges.

Conventional treatment methods such as coagulation, chlorination, and distillation have improved water quality over the years, but in this industrial era, we are faced with complex contaminants for which these methods are no longer sufficient.⁴ More advanced technologies such as nanofiltration, reverse osmosis, and membrane-based processes are more effective, but their high installation, energy, and maintenance costs make them inaccessible to developing nations,⁴ leaving the most contaminated regions the least equipped to fight it. Ensuring access to clean water for all needs and all people is therefore not only a scientific challenge but a systemic one, demanding solutions that are practical, affordable, and deployable beyond the laboratory.

Recently, adsorption⁵ and photocatalysis⁶ have emerged as more promising sustainable treatment options: versatile, chemically tailorable, and capable of targeting specific organic pollutants including dyes, pharmaceuticals, and microplastics. Yet the reliance on synthetic or commercially produced materials makes them costly and impractical across the developing world. To meaningfully advance Sustainable Development Goal 6 and ensure universal access to safe water and sanitation by 2030, chemists must look beyond the laboratory shelf. This essay proposes the use of agricultural waste, an abundant, renewable, and largely untapped resource, as a compelling pathway and a globally scalable model to deliver sustainable, affordable, high-performance water treatment where it is needed most.

Agricultural residues as high-performance, low-cost water treatment materials

Millions of tonnes of rice husks, cassava peels, groundnut shells, sugarcane bagasse, and moringa seeds are generated annually across the developing world.⁷ These wastes are rich in cellulose, hemicellulose, and lignin, whose hydroxyl, carboxyl, and carbonyl functional groups interact readily with dissolved pollutants through electrostatic attraction, hydrogen bonding, and surface complexation.⁸ Through pyrolysis, chemical activation and/or other processes, these residues can be transformed into thermally stable carbon frameworks with high surface areas and tuneable porosity,⁴ rather than being openly burned and releasing greenhouse gases and particulate matter,⁹ or left to decompose and leach organic matter into surrounding water bodies,¹⁰ compounding their contamination. The use of these agricultural wastes in water treatment therefore not only improves water quality but also interrupts a contamination cycle, advancing multiple sustainability goals through a single chemical intervention. The following sections examine how this can be achieved: firstly, through adsorption, where activated agro-waste materials capture pollutants on chemically engineered surfaces; and secondly photocatalysis, where agro-waste-derived materials transform conventional semiconductors into solar-driven degradation systems capable of mineralising complex contaminants that adsorption alone cannot destroy.

Agro-waste adsorbents for targeted pollutant removal

Synthetic dyes, pharmaceutical residues, and microplastics among others are important classes of contaminants, especially in the developing countries,⁴ for which agro-waste-based materials have demonstrated effective performance for their remediation. Since their performance depends on functionality and surface parameters, a series of tailored modifications are often carried out in order to improve those properties and remove contaminants. For dye removal, H₃PO₄-activated and carbonised mango pod removed rhodamine B with an adsorption capacity of 500 mg/g,¹¹ while KOH-activated and pyrolyzed *Nauclea diderrichii* seed epicarp removed methylene blue at 35.09 mg/g, a performance competitive with commercial materials including zeolite and carbon nanotubes.¹²

Similar performances were observed in the removal of pharmaceutical contaminants, where H₃PO₄-activated cocoa pod-derived carbon removed amodiaquine at 321.33 mg/g at a cost eight times lower than commercial activated carbon of equivalent efficiency,¹³ while a functionalised mango stone biosorbent also removed 86% of a mixed chloroquine and sertraline hydrochloride solution through faster equilibration kinetics and magnetically assisted separation.¹⁴ In microplastic remediation studies, pyrolyzed jujube leaf waste biochar achieved complete removal of nylon and polyethylene,¹⁵ and Fe co-pyrolyzed walnut shell biochar removed polystyrene at 6.75 mg/g through hydrophobic interactions and surface entrapment.¹⁶ The consistent pattern across these studies shows efficient, affordable and locally-sourced adsorbents addressing the full range of water contamination, that can be scaled to meet various needs across regions, especially in the developing world.

Agro-waste-derived materials as photocatalytic supports and synthesis agents

Heterogeneous photocatalysis using conventional semiconductors such as TiO₂, ZnO, and ferrite-based materials offers a route to complete pollutant mineralisation, however, issues including rapid electron-hole recombination, limited visible light absorption, and particle aggregation in aqueous solutions, limit their efficiency and irradiation requirements.¹⁷ Biochar from agro-waste is used as support materials to address these challenges. As an electron sink, biochar accepts photogenerated electrons from the conduction band of the semiconductor, reducing recombination and extending the lifetime of charge carriers available to generate reactive oxygen species.¹⁸ Its conjugated carbon structure also broadens light absorption into the visible spectrum, enabling solar-driven photocatalysis without artificial irradiation.¹⁹

The evidence for these combined effects is quantified in the efficiency of the resulting composite materials. A rice husk-derived biochar increased TiO₂ efficiency for bisphenol A degradation from 46.4% to 97.6% under ultraviolet irradiation,²⁰ while an orange peel biochar-TiO₂ achieved 94% acetaminophen degradation compared to 63% by the bare semiconductor under equivalent conditions.²¹ In another study, sugarcane bagasse engineered with Fe₃O₄ nanoparticles degraded 73.52% of ciprofloxacin compared to 54.57% by the pure nanoparticle, an improvement of 35%.²² For dyes, coconut shell biochar-TiO₂ degraded 99.7% of reactive brilliant blue within 60 minutes,²³ while rice husk ash combined with ZnO-CuO removed 99.9% of methylene blue.²⁴

They also serve as chemical agents in the synthesis of photocatalysts, replacing toxic chemicals with plant-derived compounds. An example is the use of onion peel extract as a reducing agent in the green synthesis of copper nanoparticles that achieved 96% degradation of methyl orange.²⁵ This is very significant, as synthesising from these local and non-toxic wastes makes local manufacturing possible in developing nations. Scaling up this solar-driven degradation using agro-waste-derived composites locally is not only possible but an important step in universal water access.

From laboratory to community: translating chemical solutions into water access

Seeing that agro-waste-derived adsorbents and photocatalytic composites have demonstrated real efficiency against a series of water contaminants, translating this research to ensure universal water access is germane. Firstly, we need to redesign research practice to simulate real environmental conditions which is complex, multi-pollutant, and variable-flow, instead of the idealised conditions under which material efficiencies are often demonstrated. This is not a minor feat however; it is a reorientation of research goals from publication to real-time deployment. This reorientation must also challenge the current incentive structure that pushes for publication output rather than the translation of scientific findings into usable solutions.

Secondly, beyond the laboratory, there is a need for government-backed policy frameworks that accelerate the adoption of proven low-cost treatment innovations, where agro-waste-based treatment is recognised. Subsidised access to these innovations, especially for small and medium-scale industries across low-income countries, is essential, as is investing in agro-waste treatment for domestic, irrigation and industrial uses. Such policy must also facilitate partnerships between research institutions, local industries, and international development organisations to bridge this gap, transforming a scientifically demonstrated solution into a commercially accessible one.

Finally, there is a need to build public trust, especially for domestic and agricultural water needs. Not only are people and industries often unaware of the treatment solutions emerging from research, many do not yet trust their credibility or safety. Chemists must go beyond the walls of the laboratory and engage directly with communities, leading discussions on the use of these innovations in treating water for various purposes. This will not only inform the public but also build trust, knowing that such discussions are being led by the innovators themselves, and that the solutions being presented are within the practical reach of the communities they are designed to serve.

Conclusions

The chemical sciences have already demonstrated, through various treatment solutions, efforts to ensure clean water for all using agro-waste based solutions as a practically effective and low-cost option. These adsorbents remove dyes, pharmaceuticals, and microplastics with efficiencies matching commercial materials at a fraction of the cost, while composites enable solar-driven degradation within a wider spectrum, with green synthesis from plant extracts that makes local manufacturing possible. While more chemical solutions can be explored, there is an urgent need for translational works into accessible, affordable, and trusted systems. Chemists, the government, industry players and the public must come together to put these solutions to work, and thereby make clean water accessible for all people and needs.

Statement on use of AI

AI was used in the preparation of this essay for improving the readability and language of the text. The AI tools used were Claude and Gemini. They were not used to produce scientific insights, to analyse or interpret data, or to draw scientific conclusions; the author accepts responsibility for the veracity and correctness of all material in this work.

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Finalist

From yellow giant to water guardian

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From byproduct to opportunity

What if one of the key solutions to global water scarcity is already being produced in excess? Every year, millions of tonnes of elemental sulfur accumulate as a byproduct of the fossil fuel industry, forming stockpiles with no clear purpose.¹ Rather than viewing this as waste, it can be reimagined as a strategically valuable chemical resource. Yet, when viewed through the lens of chemical design, sulfur has the potential to become a central component of next-generation water treatment technologies.

Water covers most of our planet,² but its availability is far more limited than it appears. Only a small fraction of the water is accessible freshwater, and even this is increasingly compromised by contamination and unequal infrastructure. Water is required for diverse needs, including drinking, sanitation, agriculture, and industry, each with distinct quality requirements. This disparity highlights a critical reality: the global water crisis is driven not only by scarcity but also by contamination, unequal infrastructure, and the limitations of existing treatment technologies. Ensuring sustainable access to clean water, therefore, requires chemical processes that are adaptable, scalable, and context-specific, rather than relying solely on conventional infrastructure expansion.³

Rethinking sulfur as a chemical resource

Addressing this challenge requires more than improving existing technologies; it demands a shift in how we conceptualize chemical resources and their role in environmental systems. One promising yet underexplored avenue lies in the sulfur cycle. The biogeochemical sulfur cycle connects atmospheric, terrestrial, and aquatic environments through transformations among different oxidation states, often mediated by microbial activity. Sulfur influences redox balance, metal mobility,⁴ and nutrient cycling. However, it is rarely considered as an active component in engineered solutions. Reframing sulfur as a controllable, designable resource that can be deliberately integrated into engineered water systems opens new directions for water treatment (Figure 1). Sulfur-based materials serve here as a representative case study of how chemical sciences can transform abundant byproducts into functional solutions. In this way, natural elemental cycles can serve not only as subjects of study but also as blueprints for technological design.

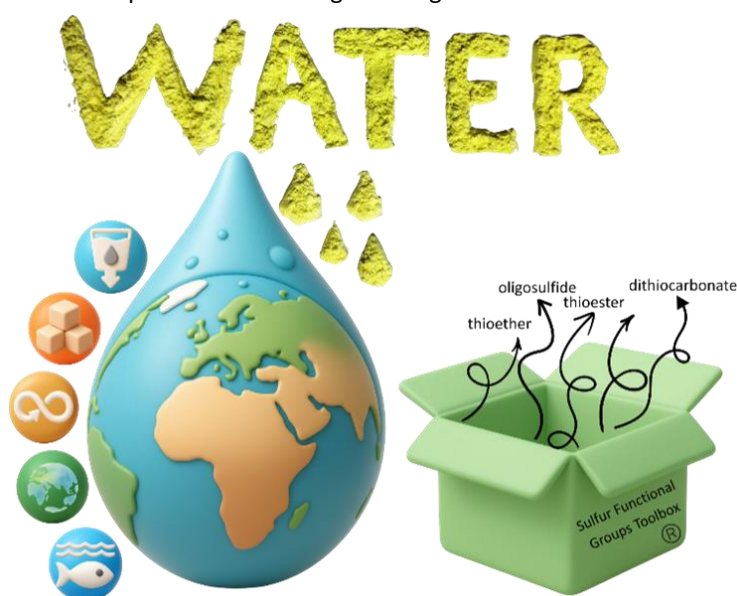


Figure 1 From yellow waste to blue water: redefining the role of sulfur functionalized materials in a sustainable future.

Overcoming chemical limitations: accessibility of sulfur

A major obstacle has been the accessibility of sulfur species in aqueous environments. Elemental sulfur (S_8), for instance, is abundant and chemically versatile but exhibits extremely low solubility in water, limiting its direct participation in aqueous reactions. Encapsulation strategies, such as incorporating sulfur into hydrophobic host systems like modified cyclodextrins, can significantly increase its effective solubility and enable its participation in aqueous redox processes.⁵ This highlights a broader principle: availability alone does not guarantee functionality; accessibility must be designed (**Figure 2**).

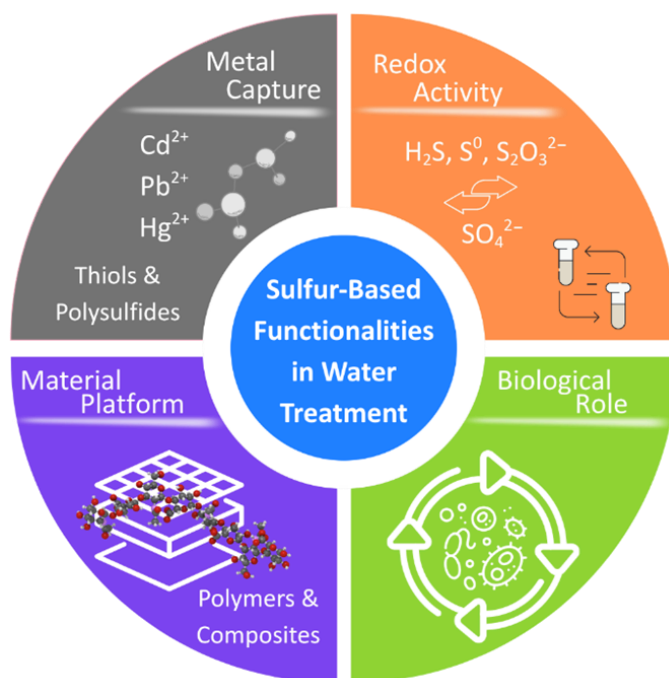


Figure 2 Schematic representation of the multifunctional roles of sulfur in water treatment, including heavy metal capture¹⁵ via sulfur functionalities, redox-driven degradation of contaminants¹⁶, integration into polymeric material platforms¹⁷, and participation in biological sulfur cycling processes¹⁸.

At the same time, sulfur chemistry offers distinct advantages for pollutant removal. Sulfur-containing functionalities⁶ such as thiols and polysulfides exhibit strong affinities for soft heavy-metal ions, including lead, cadmium, and mercury.⁷ This selectivity enables targeted adsorbent materials. Beyond adsorption, the ability of sulfur to undergo reversible redox transformations offers additional possibilities, as these transformations can be used to degrade pollutants or support coupled chemical and biological treatment processes.⁸

Sulfur-based systems, therefore, offer a promising route toward decentralized water treatment. By embedding chemical functionality directly into materials, it becomes possible to design systems that operate with minimal external input. Such systems are particularly relevant in regions lacking centralized infrastructure, where low-energy solutions are essential. These characteristics make sulfur-based materials especially suited to point-of-use technologies^{9, 10, 11} where simplicity and robustness are critical. Sulfur-functionalized materials can selectively capture heavy metals while enabling redox-driven degradation of organic contaminants, relying on intrinsic chemical reactivity rather than energy-intensive processes.

However, practical implementation requires consideration of factors beyond chemical performance, including material stability, regeneration, cost, and safe disposal. When these constraints are addressed, such systems become viable for applications ranging from rural water purification to industrial wastewater polishing. Recent advances show that sulfur reactivity can be precisely controlled through molecular design,¹² improving performance, stability, and accessibility. In particular, sulfur-based polymers, supported by sustainable synthesis methods using earth-abundant metal catalysis,¹³ demonstrate that scalable, efficient materials can be developed from abundant resources. More broadly, this approach reflects a shift in chemical thinking. Rather than viewing elemental cycles solely as natural processes, one can view them as frameworks for design. The sulfur cycle, in this context, becomes not just a subject of study but a versatile, engineerable platform for next-generation water treatment technologies. Importantly, such approaches can complement, rather than replace, existing technologies, enabling hybrid systems tailored to different water-use scenarios.

From laboratory to global impact

Taking sulfur into account is not without precedent. Sulfur-based chemistry can transition from laboratory design to urban infrastructure, even in resource-constrained settings, as demonstrated by the SANI process,¹⁴ which was piloted in Hong Kong and demonstrates that sulfur compounds can be integrated into full-scale wastewater treatment with significantly reduced sludge production. This example illustrates how chemical innovation can align with infrastructure needs and policy frameworks to deliver tangible benefits.

At a time when nearly two billion people lack access to safe drinking water, solutions that turn industrial waste into water-treatment tools represent not just chemical innovation but also a concrete step toward equitable access to clean water. Such approaches directly contribute to multiple Sustainable Development Goals (SDG), including SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water), by integrating waste valorisation, sustainable material design, and environmental protection into water treatment strategies.

To be effective globally, such technologies must be adaptable to local conditions, economically viable, and supported by appropriate governance and community engagement. Ensuring access to clean water will require solutions that are not only effective but also adaptable and scalable. Treating sulfur as a programmable chemical resource, rather than a passive environmental component, offers one such pathway. This perspective complements existing technologies while opening new directions grounded in molecular design. In this sense, the future of water sustainability may depend not only on infrastructure or policy, but also on how creatively we engage with the fundamental building blocks of chemistry. Transforming sulfur from an overlooked industrial byproduct into a tool for water purification encapsulates this shift. By linking molecular innovation with societal needs, the chemical sciences can play a central role in ensuring sustainable access to clean water for all.

Statement on use of AI

AI was used in the preparation of this essay to improve readability, language, grammar, and editorial clarity. All scientific content, interpretations, arguments, conclusions, figure design, and reference verification were developed and checked by the author, who assumes full responsibility for the accuracy and integrity of the work.

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Finalist

Opto-chemical sensors for rapid and sustainable on-site water quality analysis: breaking the 24-hour Escherichia coli barrier

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Introduction

A glass of water may appear clean, yet harmful faecal contaminants can remain undetectable to the naked eye. Consumption of such contaminated water can lead to serious waterborne diseases, including typhoid, cholera, diarrhoea and more. This hidden risk affects nearly two billion people worldwide every day.¹ It poses a major challenge to United Nations Sustainable Development Goal (SDG) 6: *clean water and sanitation*.² This challenge is particularly severe in rural regions, where conventional bacterial culture tests for *Escherichia coli* (*E. coli*) in laboratories are slow, costly, and often inaccessible.

Chemical science offers a transformative alternative through opto-chemical sensing strategies that convert molecular interactions of water contaminants into rapid and detectable optical signals. These sensors help to overcome the long-standing 24-hour bacterial testing barrier towards the development of on-site water quality analysis tools. This essay demonstrates that faecal pigments provide a chemically robust and underexplored standard for detecting faecal contamination in water. Hence, this advances SDG 6, while highlighting key challenges in achieving them in real time.

Limitations of Traditional Testing Methods and Alternative Solutions

Traditional bacterial testing methods, such as culturing *E. coli*, are accurate but often impractical for on-site use. Conventional testing for faecal contamination is often a day-long process, because bacterial growth typically requires about 24 hours.³ Bacterial testing also requires specialised laboratories and trained personnel. Alternatives to bacterial culture, such as polymerase chain reaction (PCR) and quantitative PCR (qPCR) tests, can detect bacterial deoxyribonucleic acid (DNA) more quickly. However, these tests cannot distinguish between live and dead organisms.⁴ As a consequence, this can produce false-positive results. These delays and uncertainties hinder timely decisions, making water quality monitoring a very challenging task in reality.

In response to these challenges, chemical science has identified a faster alternative molecular detection method, namely faecal pigments. These pigments are degraded products of bilirubin and are excreted by all mammals. The most common are urobilin, which gives urine its yellow colour, and stercobilin, which gives stool its brown colour. These molecular indicators offer a faster and more practical alternative to bacterial testing. Therefore, these biomarkers, commonly known as faecal indicator pigments, reliably indicate faecal contamination in water.^{5,6} These pigments coexist with faecal bacteria and correlate well with total coliform counts (**Figure 1**).⁷ Thus, faecal pigments are reliable molecular proxies for faecal contamination in water.

Ammonia (NH₃) or hydrogen sulfide (H₂S) are often used as traditional chemical alternatives to measures of faecal pollution in environmental water, but they lack diagnostic precision.^{8,9} Ammonia can enter environmental water through agricultural runoff or industrial discharge. Further, it can also be produced by various anaerobic environmental processes unrelated to faecal waste. To reduce false-positive results caused by non-faecal nitrogen sources, faecal pigments can be considered as a reliable solution. Although these pigments enable rapid on-site detection, they are best applied for initial screening and real-time faecal contaminant monitoring. Rather than replacing conventional *E. coli* analysis, these pigments serve as instant proxies for faecal contamination, complementing laboratory methods with early warning signs.

Rapid Opto-Chemical Sensing and Sustainable Deployment

These faecal pigments (tetrapyrrole molecules, **Figure 1**) exhibit weak intrinsic fluorescence.¹⁰ Chemical science offers well-established metal complexation mechanisms for enhancing fluorescence signals, e.g., Schlesinger test (1903).¹¹ This test provides a robust framework for detecting these pigments by using zinc ions to coordinate with the nitrogen atoms in the pyrrole rings.¹¹ When zinc binds to the pigment molecule, the structure becomes more rigid.⁵ This prevents energy from being lost as heat and allows the molecule to emit stronger green

fluorescence under ultraviolet light.¹² Fluorescence stability and signal intensity can be further tuned through material and chemical modifications. These improvements enable reliable on-site detection even in complex environmental samples. The impact of these molecular insights depends on how effectively they can be integrated into portable optical sensors. This strategy expands access to water quality monitoring by enabling local communities to perform routine assessments independently. For example, a smartphone-coupled three-dimensional (3D) printed optical sensor can turn a smartphone into a water-testing tool for on-site analysis of faecal contaminants.¹³

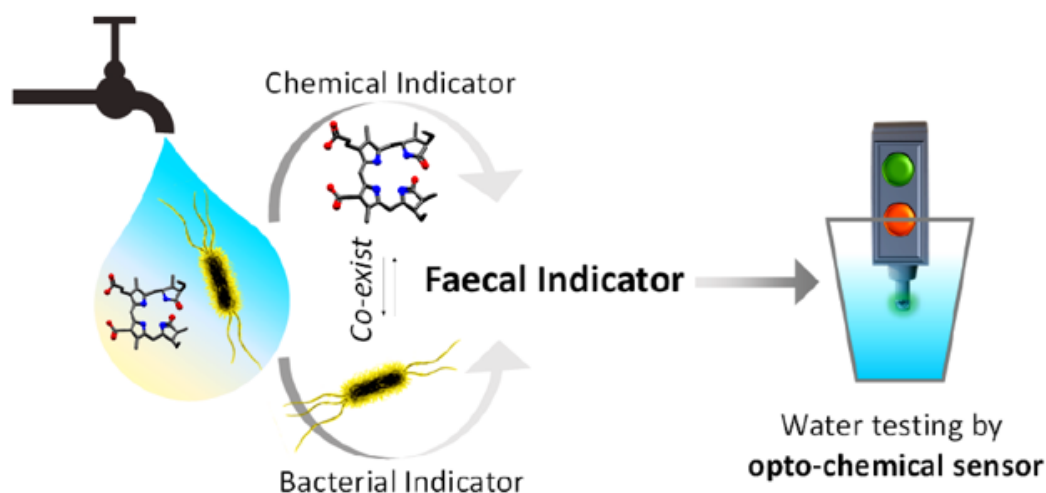


Figure 1 Illustration of faecal contamination detection in water

Even advanced sensors have a limited impact if they cannot reach end-users for on-site analysis. Additive manufacturing, also known as 3D printing, addresses this challenge by incorporating green chemistry at the design stage. The entire sensor device, including housings and optical components, can be fabricated rapidly with minimal material waste. Hence, it directly supports the principles of waste prevention and energy efficiency. Furthermore, the portable and robust sensor instrumentation is suitable for deployment in rural wells, urban pipelines, or disaster zones.

The choice of 3D printing materials is central to sustainability. By utilising bio-derived polymers such as polylactic acid or renewable photo-curable resins, chemical science reduces the carbon footprint of sensor hardware. Furthermore, the ability to print “Lab-on-a-Chip” architectures enables precise control of fluid flow at the microliter scale. This microfluidic approach ensures that the absolute minimum amount of chemical reagents is used, adhering to the “Green Chemistry” principles of waste prevention. By operating at extremely low concentrations, the system minimises the need for hazardous reagents and instead relies on non-destructive light–matter interactions. Furthermore, Open-source 3D printing enables on-demand, local production using non-toxic materials, reducing transport emissions and maintenance costs. Sustainability can also be further extended to the device’s end of life. A modular sensor design enables the reuse or recycling of electronic components, supporting circular economy principles and reducing electronic waste.

Twin transition

Rapid sensing alone is not always enough to protect communities from water contamination. Environmental waters are complex mixtures where turbidity, pH fluctuations, and dissolved organic matter can interfere with optical signals. To overcome this challenge, modern opto-chemical sensors are integrated with digital chemistry approaches that transform raw optical data into reliable environmental insights. In parallel, advances in materials chemistry enable the rational design of test-strips and membrane platforms with tuneable selectivity toward target contaminants.

This convergence of sustainable sensing technologies, data-driven analysis, and material innovation exemplifies the “Twin Transition” paradigm, where digital counterparts are seamlessly integrated. This integrated framework enables a shift of water quality monitoring from routine testing toward proactive risk management.^{14,15} Within this context, digital chemistry acts as a “virtual spectrometer,” converting raw optical signals into actionable intelligence.

Multivariate analysis, including principal component analysis and machine learning algorithms, identifies the fluorescence signal of faecal contaminants from background matrix interference in environmental water. The processed data then feeds into the digital twin, a virtual replica of the physical sensing system (Fig. 2) that updates in real time, which helps to monitor water quality efficiently. In this framework, chemometrics serves as the bridge between opto-chemical sensors and their digital counterparts.

Beyond data interpretation, the digital twin can also support sensor networks by comparing measurements across multiple devices to identify signal drift. For instance, when upstream sensors detect increasing faecal pigment levels, the model can simulate water flow to predict downstream contamination risks. Digital tools also assist sensor design: optical simulations such as ray tracing optimise light-emitting diode (LED) and lens placement within 3D-printed housing, improving sensitivity while reducing energy consumption and development costs (**Figure 2**).

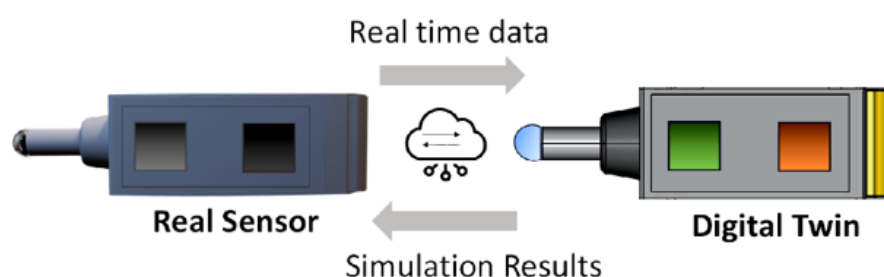


Figure 2 A simplified diagram of a digital twin assisted optical sensor for water quality analysis

Environmental, social, and economic impact

Opto-chemical sensors and digital twins can together address all three pillars of sustainability by leveraging various tools from chemical science for water quality monitoring.

Environmental sustainability: Low-resource approaches like paper-based assays, colourimetric strips, and smartphone-integrated devices reduce toxic chemical waste. 3D printing allows local, on-demand production and cuts transport emissions.

Social equity: Sensors translate complex chemistry into actionable insights, so communities do not depend on scientific labs or specialists. Real-time information empowers end-users to take control of their health and hygiene.

Economic feasibility: The integration of 3D-printed opto-chemical sensing into on-site water quality analysis is also cost-effective. Traditional laboratory testing incurs high sample costs due to logistics and specialised labour. This enables frequent monitoring while reducing long-term testing costs for utilities and local communities.

This vision directly addresses *SDG 6 (Clean Water and Sanitation)*, and its impact extends beyond it. Rapid, on-site water testing reduces exposure to waterborne pathogens, supporting *SDG 3 (Good Health and Well-being)*. At the same time, affordable, sensing technologies reduce diagnostic inequalities between urban and low-resource settings, advancing *SDG 10 (Reduced Inequalities)*.

Conclusions

Chemical science now provides tools that transform water quality monitoring from slow laboratory-based testing into rapid, on-site analysis. Thus, communities can detect water contamination directly at the point of need by combining faecal pigment sensing, 3D-printed optical devices, and digital chemistry. This approach not only overcomes the long-standing 24-hour *E. coli* testing barrier but also empowers local stakeholders, reduces environmental impact, and advances equitable access to safe water. Looking forward, these strategies can be extended to emerging water contaminants such as microplastics, per- and polyfluoroalkyl substances (PFAS), and heavy metals. Hence, it supports global efforts to safeguard public health while addressing multiple *Sustainable Development Goals*. In doing so, chemical science moves beyond measurements, providing practical solutions that bring clean water within reach for all.

Statement on use of AI

AI was used in the preparation of this essay to check the grammatical errors and readability. AI was not used to analyse data, draw scientific conclusions or provide references that do not exist. After using this tool/service, the author reviewed and edited the essay as required and takes full responsibility for the publication.

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Finalist

Heterogeneous electro-Fenton process for wastewater treatment: one for the future

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More than a century ago, Henry Fenton discovered that hydrogen peroxide (H_2O_2), although inactive alone, was capable of vigorously oxidizing tartaric and similar acids in the presence of ferrous salts.¹ Later, Fritz Haber & Joseph Weiss proposed that the hydroxyl radical ($\cdot\text{OH}$) was responsible for the extraordinary oxidizing power of the H_2O_2 -ferrous (Fe^{2+}) mixture.² This mixture was subsequently referred to by researchers as Fenton's reagent, while the associated chemical reaction became known as the Fenton reaction. Nevertheless, Fenton's reagent received only sporadic attention in environmental applications until the groups of Brillas and Outran popularized it in the 1990s.^{3,4} In contemporary research, this classical chemical reaction serves as the backbone of many advanced oxidation processes for treating complex contaminants commonly detected in wastewater.

Over the years, the integration of electrochemistry with the classical Fenton reaction gave rise to the electro-Fenton (EF) process, enabling the *in situ* and continuous generation of Fenton's reagent for wastewater treatment (**Figure 1**). Pioneered by Prof. Brillas, this electricity-driven process fundamentally uses only electrons (e^-) as the primary reactant.³ In EF, a selective cathode (often carbon-based) that can perform the $2e^-$ oxygen reduction reaction (ORR) is employed to electro-generate H_2O_2 in oxygen (O_2)-fed bulk solution (Eq. 1). Subsequently, a small amount of Fe^{2+} salt is introduced for triggering $\cdot\text{OH}$ generation through catalytic decomposition of H_2O_2 (Eq. 2). These highly reactive $\cdot\text{OH}$ species then non-selectively oxidize organics in wastewater or a target contaminant in a more controlled system (Figure 1). Notably, Fe^{2+} addition is required in catalytic amounts, as Fe^{3+} can be continuously reduced to Fe^{2+} at the cathode (Eq. 3). Since Fenton's reagent is electrogenerated, the EF system has minimal external chemical requirements, and stubborn contaminants are spontaneously degraded due to copious and uninterrupted $\cdot\text{OH}$ production. These salient features led to a surge in the application of the EF system for treating a wide spectrum of problematic contaminants and wastewater in the first decade of the 21st century.⁵

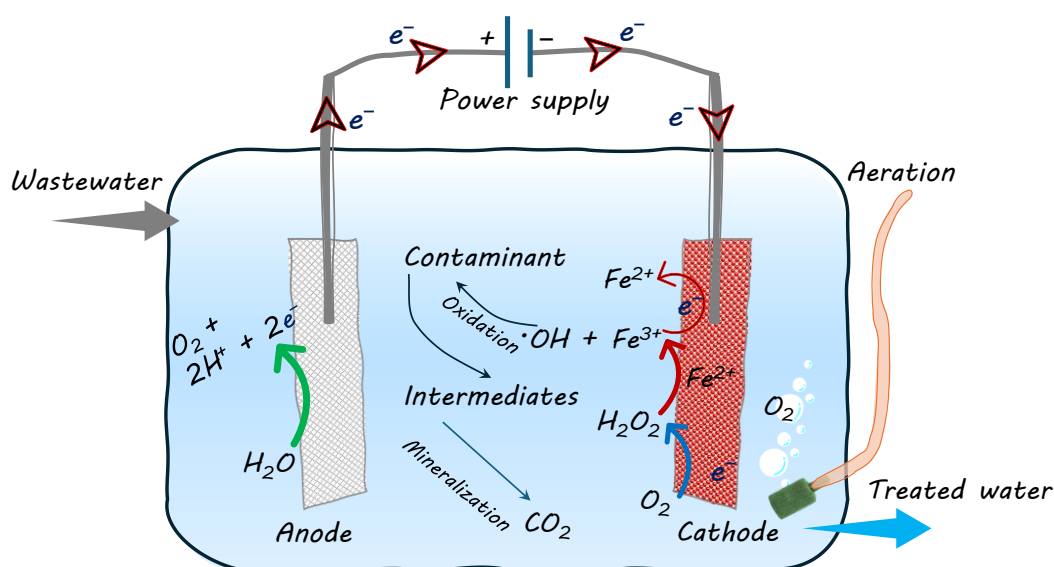


Figure 1 Schematic of the mechanism of the electro-Fenton process

However, these systems were mainly limited by sluggish ORR, a poor ferric (Fe^{3+}) to Fe^{2+} redox cycle, and a strict pH requirement (~ 3.0), making upscaling challenging. Therefore, the next developmental stages of EF focused on material science and chemistry to overcome these limitations. Consequently, extensive research on solid catalysts that can be functionalized on the cathode to boost ORR and $\cdot\text{OH}$ generation ensued. Such EF systems, which employ a solid catalyst rather than Fe salts, are referred to as heterogeneous electro-Fenton (HEF) processes. HEF boasts several advantages over conventional EF, including a broader working pH range, reduced catalyst loss, stable and prolonged operation, and the absence of secondary pollution from excess dissolved Fe in the treated wastewater.⁶ In HEF, metal (usually Fe) in conjunction with a carbon substrate are considered well suited for this purpose. Carbon materials are selective for the 2e^- ORR pathways, generating H_2O_2 under applied cathodic potentials. This property can be augmented by morphological modifications (specific surface area, porosity, and structural defects), introduction of oxygen functional groups (e.g., $-\text{COOH}$) on the carbon surface, and heteroatom doping (e.g., nitrogen and boron).^{7,8}

Meanwhile, the metal centres in the carbo-metallic catalyst can facilitate the transformation of H_2O_2 to $\cdot\text{OH}$. Iron-based materials, such as oxides, sulfides, and zero-valent nanoparticles, are considered ideal due to their high activity, non-toxicity, and abundance. However, composites with other metals, such as Mn, Ni, Co, and Cu, support radical activation and provide stability by preventing Fe leaching during the electrochemical process.⁹ Further, doping with heteroatoms, especially nitrogen (N), enhances electronic conductivity, stabilizes Fe on the carbon substrate by forming $\text{Fe}-\text{N}_x-\text{C}$ coordination sites, and boosts ORR by improving the adsorption of molecular O_2 on the catalyst surface and promoting $\text{Fe}^{3+}/\text{Fe}^{2+}$ redox cycling.¹⁰⁻¹²

These advances in materials science and catalysis have made the HEF process highly effective destroying very recalcitrant contaminants and persistent pollutants, such as microplastics, per- and polyfluoroalkyl substances (PFAS), and similar persistent organic compounds.^{10, 13, 14} In fact, high degrees of mineralization ($\geq 90\%$), representing the complete breakdown of contaminants into carbon dioxide and innocuous products, have been demonstrated by HEF.^{15, 16} Higher mineralization ensures that treated water does not contain toxic intermediates or oxidation byproducts, thereby safeguarding against secondary contamination. Moreover, the development of advanced cathode and catalyst materials has expanded EF applications to real wastewater streams at the pilot scale.¹⁷⁻¹⁹ In one case, the cost of treating industrial wastewater was reported to be as low as US\$0.9 per kg of chemical oxygen demand, making it competitive with existing wastewater treatment technologies.¹⁹ These pilot-scale EF investigations showcase the gradual ascent of the technology up the technology readiness level (TRL) ladder.

Since its inception, the Fenton process has come a long way in terms of process design and material development (Figure 2). At present, the trajectory in HEF research is to further enhance its economic viability by developing high-activity, inexpensive catalysts and by coupling HEF with photo- and bio-based systems to maximize energy efficiency. Lately, the application of single-atom and dual-atom catalysts (SACs and DACs) has become a frontier in Fenton catalysis. Unlike bulk or nanoparticle catalysts, in which metal atoms exist as clusters with limited exposed active sites, these state-of-the-art catalysts feature atomically dispersed single metal atoms anchored on heteroatom-doped carbon substrates, offering exceptional metal atom utilization efficiencies, tuneable electronic structures, and adaptable coordination geometries.²⁰ SACs are typically synthesized as $\text{Fe}-\text{N}$ ensembles embedded in porous carbon matrices (denoted as $\text{Fe}-\text{N}-\text{C}$), with robust $\text{Fe}-\text{C}$ and $\text{Fe}-\text{N}_x$ moieties that serve as the active centers. $\text{Fe}-\text{C}$ sites play a key role in H_2O_2 electro-generation, whereas $\text{Fe}-\text{N}_x$ sites facilitate H_2O_2 activation to $\cdot\text{OH}$ and other reactive species.²¹

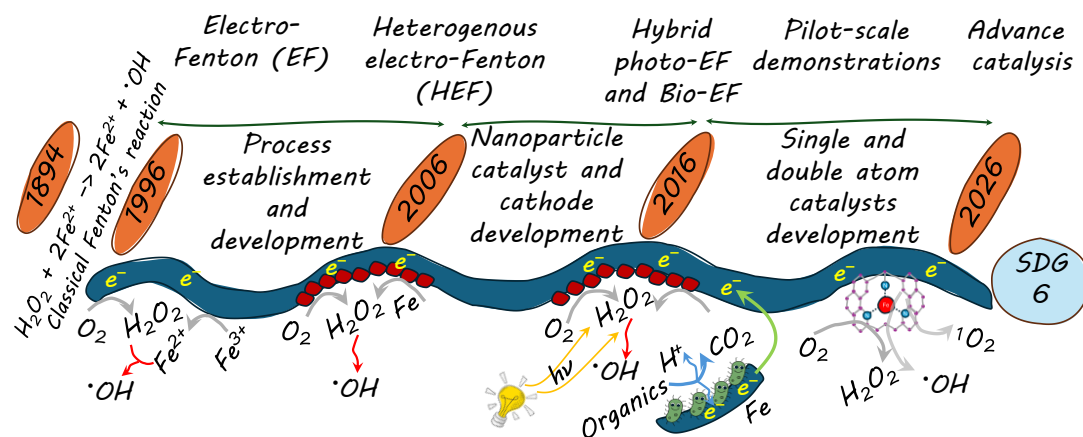


Figure 2 Advancement in the electro-Fenton process for wastewater treatment.

Meanwhile, in DACs, an additional neighbouring metal atom is introduced adjacent to the Fe centre of SACs, enabling cooperative catalysis and enhancing performance.²² To curtail the synthesis costs and associated environmental footprint, alternative green synthesis routes are being explored for both bulk and atomic catalysts. Naturally abundant biomass, metal-rich algae, and wastewater sludge have been used as precursors for the synthesis of Fe–N–C coordinated catalysts.^{23–25} In addition to economic benefits, waste-derived catalyst can reduce the life-cycle impacts of the entire water treatment process.²⁴ Researchers are now employing advanced computational techniques, such as density functional theory (DFT), to understand intricate catalyst behaviour at the molecular level.²² When coupled with experimental results, these tools can help further tailor catalyst design to suit specific environments and requirements.

Among hybrid approaches, the photoelectron-Fenton (PEF) and bioelectro-Fenton (BEF) processes are the most promising techniques. In the PEF system, the photoactive electrode is illuminated to generate additional photogenerated electrons, accelerating the $\text{Fe}^{3+}/\text{Fe}^{2+}$ cycle and promoting the production of additional reactive species, thereby enhancing pollutant removal.²⁶ In contrast, in BEF systems, a microbial fuel cell is modified to perform an EF-like reaction at the cathode.²⁷ This novel system does not rely on external power sources and operates on electricity generated by the biological metabolism of organics by electroactive microorganisms colonizing the anode chamber. However, these hybrid systems are still at a nascent stage, with considerable scope for further process improvement. Another overlooked roadblock to HEF upscaling is the continuous aeration requirement to ensure dissolved O_2 availability for the 2e^- ORR. Aeration energy consumption can be tens of times higher than the energy required for the electrochemical reactions themselves.²⁸ Innovative strategies, such as gas diffusion and natural O_2 -harvesting electrodes, which utilize O_2 from the atmosphere or from the anode (generated via the ORR), eliminate the need for artificial aeration.^{28, 29}

Undoubtedly, HEF has emerged as a reliable strategy for treating recalcitrant compounds and wastewater. Given the intensifying stress on freshwater reservoirs and their contamination by persistent organic pollutants, there is an urgent need to develop effective, cost-efficient treatment solutions. The HEF process offers significant advantages and is a promising approach to addressing this critical challenge. The process has demonstrated considerable efficiency in eliminating problematic pollutants and, with slight modifications, can be employed to treat a variety of wastewater streams. With increasing pilot-scale investigations, HEF may now be considered to have reached an intermediate TRL (4–6).^{30, 31} Continuous efforts are being made to make the HEF process more economically and environmentally viable by using high-activity catalysts synthesized from waste-derived sources and hybrid systems. Advances in catalyst materials technology have improved HEF performance by leaps and bounds, while rapid progress in atomic-level characterization and sophisticated theoretical modelling and simulations has helped decipher the complex catalytic mechanism of HEF. These insights can be used to engineer HEF systems for broader mainstream applications. Furthermore, as the world shifts towards renewable energy, HEF systems may become more competitive with contemporary wastewater technologies, accelerating their real-world adaptation. In the near future, HEF-based technologies could be instrumental in the transition to a sustainable society, achieving United Nations Sustainable Development Goal 6, and ensuring global water security.

Statement on use of AI

Artificial Intelligence (AI) tools were used to improve the clarity, readability, and coherence of this essay (Grammarly). Following their use, the author carefully reviewed and revised the content as necessary and assumes full responsibility for the final version of the work.

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Finalist

***From natural minerals to programmable frameworks:
the evolution of adsorption chemistry
for sustainable water access***

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The chemical sciences fundamentally challenge the common misconception that clean water is a “free” or inexhaustible resource; rather, analytical and materials chemistry reveal that potable water is an increasingly rare and sophisticated product of high-precision engineering. While raw water may be physically accessible in some regions, its status as a primordial resource for civilization is being severely compromised by rapid industrialization and population growth, and other geopolitical concerns.^{1–3} From a chemist’s perspective, the “clean water” of the past is being replaced by complex aqueous mixtures of municipal, industrial, pharmaceutical, and agricultural waste that require advanced monitoring and remediation.²

Global water security is diagnosed, and remedial actions are offered through chemistry. Through the rigorous application of analytical chemistry, and different advanced chemistry applications for the removal, reduction, or neutralization of hazardous substances. Diagnosis is done by aggregating diverse parameters such as pH, Total Organic Carbon (TOC), biological oxygen demand (BOD), and specific concentrations of nitrates and phosphates into a single score using Water Quality Indices (WQI).^{1–5} It is used to translate complex environmental datasets into actionable intelligence, identifying core contaminants that threaten human health. The WQI score classifies water into quality classes: Class I is very good, and Classes V and VI are the most polluted and are generally considered unusable for drinking unless subjected to intensive, specialized, advanced treatments.^{1,5} After categorizing water into quality classes, remediation is done via advanced material chemistry, ensuring that purification means are both sustainable and effective. Once the quality classes are identified, physical, chemical, and biological processes could be used to ensure sustainable access to clean water.^{5–7}

The water quality challenges identified reflect a global pattern of anthropogenic pressure. In the Prut River, Romania, TOC was detected at high levels (up to 158.98 mg/L exceeding the target threshold of 5 mg/L) dangerous because the residual organic matter reacts with chlorine during disinfection to form trihalomethanes, which are known carcinogens.² In the Kalu River, Sri Lanka, assessments reveal high phosphate levels due to agricultural runoff, and alarming chloride concentrations near urban centres caused by saltwater incursion. WQI assessments of the Kelani River, Sri Lanka, identified that the water is unfit for drinking,⁸ emphasizing the need for legislative actions against industrial effluents in Sri Lanka.⁴ Studies of the Topolnita and Kor Rivers in Bulgaria and Iran further validate the use of chemical indices to manage the impacts of mining and industrial waste on surface water.^{4,9}

Primary concern in surface water monitoring is often the presence of residual organic matter, which reacts with chlorine during disinfection to produce trihalomethanes, a potential carcinogenic compound.² When WQI characterizes the water as “Class IV” or “Medium Quality”, advanced material sciences dictate the treatment steps, most notably adsorption technology. Adsorption is favoured in the chemical community because it offers a “clean” path to remediation; unlike coagulation, it sequesters pollutants onto a solid phase without generating massive volumes of secondary sludge.^{6,10,11}

Adsorption is one of the definitive chemical technologies for removing pollutants at trace levels. It relies on attractive forces, including Van der Waals Forces (physisorption), hydrogen bonding, acid-base interactions, and π - π interaction (Chemisorption) between the adsorbent (solid phase) and the adsorbate (liquid phase). Quantification of the rate at which adsorbate molecules adhere to the adsorbent is known as Adsorption kinetics.^{6,7,12} This provides essential insights into the speed of the purification process and the underlying reaction mechanism. Adsorption isotherms describe the equilibrium distribution of pollutants between the adsorbent and the solution at a constant temperature, to determine the adsorbent’s maximum loading capacity via mathematical models like the Langmuir or the Freundlich equations.^{6,11} These two concepts allow the precise optimization of high-performance frameworks to ensure the sustainable and efficient removal of emerging bio-recalcitrant contaminants from global water suppliers.

The pursuit of sustainable water access, reveals a profound chemical arc: the transition from the utilization of bulk natural minerals to the era of atomic design. This evolution represents the triumph of the chemical

sciences in translating the fundamental molecular interactions into scalable technologies that ensure clean water for all human needs.

The earliest iteration of water treatment, exemplified by the traditional use of clay pots in South Asian households, relies on the inherent physicochemical properties of aluminosilicate minerals. While traditionally valued for their cooling properties, these materials represent the foundational use of natural adsorbents like zeolites and montmorillonite. Principle is governed by the ion exchange and surface adsorption within a porous mineral matrix.¹¹

Natural clays possess a significant cation exchange capacity, allowing for the capture of larger ions from aqueous solutions. Modern analytical chemistry has categorized these as “Class III” or “Class IV” interventions, where the natural mineral surface acts as a primary barrier against bulk contaminants. However, natural clays often suffer from low selectivity and are easily eclipsed by high concentrations of competing ions in the modern complex water systems.^{3,5,11}

The 20th century marked a significant shift toward engineered carbonaceous materials. Activated carbon has served as the definitive industrial workhorse since the 1920s for colour and taste removal, and since the 1960s for tertiary wastewater treatment.¹¹ Its effectiveness is derived from a high specific surface area and a complex network of micro- and mesopores that facilitate physical adsorption via Van der Waals forces. Despite its reliability, activated carbon remains a relatively heterogeneous material with limited molecular specificity, often requiring energy-intensive regeneration processes.^{7,11}

The advent of nanotechnology has moved beyond bulk properties to molecular-scale manipulation. Nano-hydroxyapatite (nano-HAP) ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) has emerged as a quintessential “green” adsorbent due to its hexagonal crystal structure and biocompatibility. Its chemical action is versatile, utilizing multiple simultaneous mechanisms. Through the ion exchange process, foreign divalent cations like Pb^{2+} or Cd^{2+} replace Ca^{2+} in the crystal lattice. Active sites on the nanoparticle surface form stable complexes with heavy metals and radionuclides. The final technique would involve nano-HAP forming even more stable, partially soluble phases, effectively mineralizing pollutants via dissolution-precipitation.¹⁰

Nano-HAP offers staggering removal rates for trace-level contaminants or even complex organic chemistries like Rhodamine dyes contamination, in the textile industry wastewater.¹³ However, their industrial application is hindered by the tendency of nano-HAP to agglomerate, which is overcome by dispersing them in biopolymer matrices like chitosan or alginate to create high-performance hybrid composites.^{6,10}

The development of Metal Organic Frameworks (MOFs) represents the pinnacle of coordination chemistry, where metal nodes and organic linkers are assembled with atomic precision to create purposeful, strong bonds designed to have porous structures with atomic precision. Unlike heterogeneous traditional adsorbents, MOFs are constructed from metal nodes and organic linkers that form strong, purposeful bonds.^{15,16}

MOFs transcend limitations of all previous chemistries by offering tuneable pore sizes and functionalized surfaces that can be designed for specific molecular targets. This allows for unprecedented functions, such as the ability to pull pure drinking water directly from desert air – a literal “science of hope” for water-stressed regions. The Nobel laureate Omar M. Yaghi explains that atmospheric water harvesting using MOFs begins with the adsorption of moisture into their porous crystalline structures until sufficient concentration is achieved. The captured water is then released through temperature or pressure-induced desorption and subsequently condensed into liquid potable water via passive or active cooling.¹⁷ In water purification, MOFs can be designed with multiple choices of metal nodes (Zinc, Copper, Zirconium, Chromium, or Transition metals like Cobalt, Nickel, and Ferrous), each designed to adsorb different types of contaminants. Choice of these metal nodes is not merely aesthetic; it defines the “Lewis acid” character of the framework’s surface. For example, the hard Lewis acid nature of metals like Zirconium often facilitates stronger coordination with pollutants containing oxygen or nitrogen, ensuring high removal efficiencies even at trace levels.¹⁵

In the pursuit of sustainability, low-cost agricultural waste as biosorbents being widely discussed. Materials such as sugarcane bagasse and biochars derived from date palms demonstrate significant potential for removing COD and heavy metals like Uranium and Lead from industrial wastewater.¹²

Despite the proliferation of high-performance materials in scientific literature, industrial implementation remains focused on a handful of traditional adsorbents. The challenge today is to overcome non-technical barriers, such as high cost and complexity of scaling up MOF synthesis.¹⁵ A strategic drive would be a revision of regulatory frameworks, such as the 2024 European Union directive on urban wastewater, which mandates the removal of 80% organic micropollutants, serving as a critical catalyst for the deployment of these advanced chemical technologies.⁷

In conclusion, the chemical sciences ensure sustainable access to clean water by providing a continuum of precision: from the analytical WQI that identifies molecular threats to the advanced MOF architectures that capture and transform them. Through the refinement of adsorption kinetics and the development of resource

recovery processes – where nitrogen and phosphorus are recaptured from wastewater – chemistry transforms treatment facilities into essential hubs of a circular, water-secure economy.

Statement on use of AI

During the preparation of this work, AI tools Grammarly and ChatGPT were used to improve the clarity and flow of this essay. The author reviewed and verified all the content for scientific accuracy and takes responsibility for the final text.

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Finalist

Mitigating pesticide-derived water contamination through chemical innovation

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Introduction

The agricultural sector is the primary source of food for the population of the world, and ongoing population growth is driving a continuous increase in food production demand.¹ However, many crops are affected by pests that damage crops during growth, harvest, or storage. These pests include insects, fungi, weeds, bacteria, and viruses that cause damage or disease to crops, leading to significant losses in food production.² Each year, more than 40% of global crop production is lost due to plant pests and diseases.³ To mitigate these losses, pesticides have been used for decades. In 2022, approximately 3.7 million tons of pesticides were used worldwide.⁴

Pesticides are substances or mixtures of substances intended to prevent, destroy, repel, or mitigate organisms considered pests. Depending on the target pest, different types of pesticides exist, such as insecticides, fungicides, herbicides, and others.⁵ Commercial pesticide products are formulations usually composed of one or more active ingredients and additional substances known as adjuvants or co-formulants.⁶ The active ingredients are molecules that exert the biological effect against the target pest.⁷ To improve application efficiency, solubility, stability, absorption, and action of the active ingredient, adjuvants are incorporated into pesticide formulations.⁸ The most common adjuvants present in commercial pesticide products include solvents, surfactants, emulsifiers, pigments, antifreeze agents, and carriers.⁹

Despite their effectiveness in crop protection, pesticides pose significant environmental challenges. The high content of adjuvants in conventional formulations can lead to adverse effects on soil texture and plant productivity¹⁰, as well as reduced nutritional quality of fruits and potential risk to human health.¹¹ Furthermore, both active ingredients and adjuvants can be transferred from the target site to other environmental compartments through processes such as leaching, volatilization, spray drift, and runoff, resulting in the contamination of groundwater and surface water bodies, and compromising water quality.¹²

The presence of these compounds in the environment can promote the development of pest resistance, reduce the diversity of beneficial microorganisms, and negatively affect non-target organisms, including humans.¹³ Therefore, the use of pesticides represents a critical challenge for ensuring sustainable access to clean water.

Addressing this issue requires not only improved management practices but also the development of safer and more efficient agrochemical systems. In this context, the chemical sciences play a central role in designing sustainable crop protection strategies. In particular, pesticide-derived water contamination can be mitigated through chemical innovation, including the development of novel active ingredients and natural- and nanomaterial-based delivery systems that reduce environmental dispersion and persistence.

Chemical strategies to mitigate pesticide-derived water contamination

Given the environmental and health risks associated with synthetic active ingredients and conventional adjuvants, nanomaterials have been proposed as safer and more sustainable chemical strategies for pest control.¹⁴

A wide range of nanomaterials, including carbon nanostructures, metal- and metal oxide-based nanoparticles, and biopolymer-based nanomaterials, have demonstrated activity against insects, fungi, bacteria, and nematodes under laboratory conditions.¹⁵ As a result, these materials have been explored as active ingredients in nanopesticide formulations. Compared to conventional pesticides, nanopesticides exhibit enhanced physicochemical stability, improved interactions with biological targets, and greater efficacy due to their reduced particle size and high surface area.¹⁶

In addition to their role as active ingredients, nanomaterials have also been investigated as adjuvants for pesticide delivery.¹⁷ In particular, nanoporous materials are the most promising platforms for advanced pesticide formulation due to their tuneable pore structure, large surface area, and capacity for controlled loading and release of active compounds.⁹ These systems provide precise and controlled release of pesticides, enhance their stability under environmental conditions, and improve adhesion and permeability in plant tissues.¹⁸ For

example, nanopesticides based on mesoporous silica nanoparticles (MSNs) have demonstrated improved stability and delivery efficiency of antifungal compounds. Xu et al.¹⁹ developed a pH-responsive pesticide delivery system based on MSNs and chitosan for the controlled release of tebuconazole. Similarly, Kaziem et al.²⁰ developed an enzyme-responsive delivery system from MSNs and β -glucan for the controlled release of captan. These stimulus-responsive systems allow for more precise control over pesticide release, reducing excessive application and minimizing the accumulation of chemical residues in soil and water environments.

In addition to nanotechnology-based approaches, compounds derived from natural products, including derivatives and synthetic mimetics, have emerged as an innovative and sustainable strategy for crop protection.²¹ Natural products are chemical compounds produced by living organisms mainly through secondary metabolism. These molecules play an essential role in defence mechanisms against predators, pathogens, and environmental stress.²² Due to their extensive structural diversity and biological activity, natural products represent a valuable source for the discovery and development of new pesticides.²³

These compounds can be directly used as active ingredients in pest control. For example, Liu et al.²⁴ isolated diphenyl ethers produced by the fungus *Aspergillus versicolor*, which exhibited strong antifungal activity against *Golovinomyces cichoracearum*. In other cases, natural products can be used as structural templates for the design of novel synthetic analogs with improved properties. For instance, Zhang et al.²⁵ synthesized derivatives of tenuazonic acid, a natural phytotoxin produced by the fungus *Alternaria alternata*, which exhibited broader-spectrum herbicidal activity than atrazine. Similarly, Zhou et al.²⁶ developed a derivative of ethyl 3-phenyl-2,3-dibromopropionate, a natural compound isolated from the bark of *Pinus contorta*, which showed antifungal activity comparable to that of azoxystrobin against *Alternaria solani*.

These compounds are considered more environmentally compatible than conventional synthetic pesticides due to their low toxicity and unique modes of action, which can also reduce the likelihood of resistance development.²⁵ Additionally, their rapid environmental degradation decreases the risk of accumulation in soil and water systems, thereby contributing to the protection of groundwater and surface water quality.²⁷

Beyond their role as active ingredients, natural compounds can also function as adjuvants in pesticide formulations. In particular, biosurfactants, such as glycolipids, lipopeptides, phospholipids, polymeric surfactants, and fatty acids, are amphiphilic molecules capable of reducing surface tension and enhancing the dispersion and uptake of active ingredients.²⁸ These compounds are produced by microorganisms, including bacteria and fungi, and offer several advantages over conventional surfactants, such as lower toxicity, higher biodegradability, and stability under extreme environmental conditions of temperature, pH, and salinity, making them promising candidates for the development of more sustainable and environmentally compatible pesticide formulations.²⁹

Conclusions

Pesticide-derived water contamination represents a significant challenge to achieving sustainable access to clean water. The chemical sciences offer effective tools to address this issue through the development of innovative agrochemical systems, including novel active ingredients and delivery systems based on natural compounds and nanomaterials. These approaches can reduce the environmental dispersion, persistence, and toxicity of pesticides while maintaining their efficacy in crop protection. Integrating chemical innovation with sustainable agricultural practices will be essential to minimizing water contamination.

Statement on use of AI

AI were used in the preparation of this essay for linguistic revision and to improve the clarity and readability of the manuscript.

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Finalist

Green Pesticides, Clean Water: Redesigning Agrochemicals for Environmental Safety

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Introduction

With the global population projected to reach 9.7 billion by 2050, the demand for increased agricultural productivity has become paramount.¹ Pesticides remain an indispensable tool for safeguarding yields against pests and diseases, ensuring that such chemical interventions remain inextricably linked to agricultural systems for the foreseeable future.² However, pesticide use extends far beyond agricultural targets, posing a pervasive threat to the global environment. Currently, nearly one-third of the world's regions are classified as being at high risk of pesticide-induced pollution.³ Among the most pressing environmental challenges is the contamination of freshwater resources through pesticide drift, runoff, and persistence, a trend that directly imperils the achieves of SDG 6.⁴ Research data reveals a concerning breach of safety standards in parts of Africa and Asia, where over 50% of water samples exceed permissible pesticide thresholds.⁵ Under the *Stockholm Convention*, most organochlorine pesticides are recognized as persistent organic pollutants that imperil both human health and the stability of non-target ecosystems.⁶ While global efforts are underway to quantify these risks and develop remediation strategies,⁷⁻¹⁰ ensuring sustainable access to clean water while maintaining crop protection remains a critical challenge (**Figure 1**).

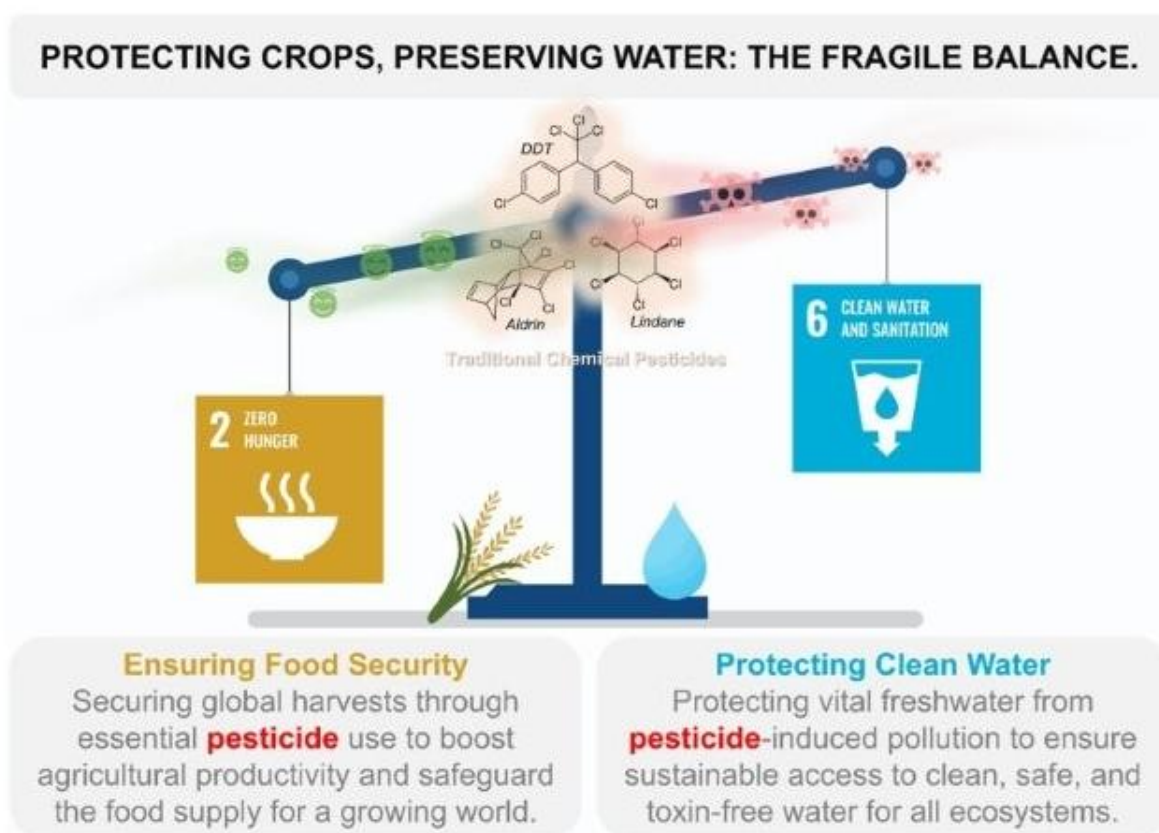


Figure 1 Balancing agricultural productivity and water security: the conflict between pesticide application and freshwater sustainability.

The concept of "green" pesticides has emerged as a solution – these are pesticides designed to be safe, effective, and biodegradable, with minimal adverse effects on the environment.¹¹ From the standpoint of addressing the fundamental drivers of water scarcity caused by pesticide pollution, the development of green pesticides featuring tuneable degradation kinetics and negligible ecotoxicity represents a strategic imperative for sustainable agriculture.¹² Unlike conventional synthetic toxicants, green agrochemicals are characterized as "benign by design", a framework that facilitates effective pest management while precluding persistent environmental contamination.¹³

Water-safe design principles for green pesticides

Discovering bioactive natural products as green pesticides: A key pillar of green pesticide development is the identification of naturally occurring molecules with pesticidal properties.¹⁴ Contemporary green pesticides encompass a diverse range of biopesticides, including microbial agents such as *Bacillus thuringiensis*, *Beauveria bassiana*,¹⁵ biochemical pesticides like plant-derived azadirachtin or lepidopteran-targeted pheromones for mating disruption,^{16,17} and emerging RNA interference-based products that leverage highly sequence-specific dsRNA to target essential genes in pests like the corn rootworm.¹⁸ These substances are typically characterized by high selectivity, inherent biodegradability, and minimal environmental persistence. Their identification leverages evolutionary ecology, focusing on organisms with potent defensive secondary metabolites.¹⁹ Unlike their synthetic counterparts, these natural products have co-evolved to undergo rapid environmental attenuation, thereby mitigating the risks of bioaccumulation and aquatic toxicity.

Benign-by-design and structural redesign for degradability: In addition to natural options, many synthetic green pesticides are created through targeted molecular engineering, ensuring that the resulting structures prioritize both pest-control efficiency and environmental safety.¹² This strategy embraces a nature-inspired molecular design that integrates fermentation and synthetic pathways, ensuring a highly sustainable industrial cycle characterized by degradation products with negligible ecological footprints.²⁰ Specifically, accelerated degradation kinetics and the resulting reduction in bioavailable concentrations within water bodies significantly lower the ecotoxicological risk of the system. The integration of predictive frameworks, such as QSAR modelling and artificial intelligence-aided toxicity predictions, empowers researchers to pre-screen molecular candidates with green potential during the nascent stages of development.²¹ This benign-by-design ensures the security of global water systems by preventing residue accumulation and reducing mammalian exposure risks.

Advanced formulations for environmental release control: Green design principles are not confined to the initial molecular engineering phase but rather necessitate meticulous refinement of the formulation to ensure maximum efficacy and ecological safety. Current research underscores that nano-agrochemicals offer superior target permeability and precision delivery, effectively mitigating off-target dissipation and environmental loss.²² By leveraging advanced carrier materials, these formulations can be engineered with sustained-release profiles that are responsive to specific environmental factors and biological microenvironments. The encapsulated active ingredients remain protected throughout the delivery trajectory, which culminates in the carrier responding to site-specific chemical or biological triggers to modulate its porosity or undergo programmed degradation for a controlled release.²³ These design innovations reduce the chances of excess chemicals reaching water bodies.

Efficacy versus environment trade-offs: As illustrated in **Table 1**, unlike traditional persistent chemicals, green alternatives such as spinosad and pheromones provide highly effective pest control with minimal ecological residence times. Although the quest for inherently non-toxic substances is often viewed as an aspirational limit, the principle that efficacy and degradability are synergistic remains a cornerstone of long-term development.²⁰ Modern agrochemical engineering strives to achieve high-performance pest control coupled with accelerated environmental dissipation, effectively mitigating aquatic pollution risks.

Table 1 A comparison between traditional chemical pesticides and green pesticides

Pesticide	Origin	Target pests	Typical environmental persistence	Water & non-target impact	Refs
DDT	Synthetic organochlorine	Broad-spectrum insecticide	Very persistent: approximately 20 years or even longer.	Bioaccumulates; highly toxic to fish, birds; persistent in sediments.	24
Imidacloprid	Synthetic neonicotinoid	Aphids, whiteflies, termites	Moderate-high: persists in soil up to 1 year; mobile in water.	High toxicity to aquatic invertebrates; found in surface/groundwater.	25
2,4-D	Synthetic herbicide	Broadleaf weeds	Low-moderate: ~6-15 days (aerobic); up to 300 days (anaerobic)	Low bioaccumulation; can leach into groundwater.	26
Spinosad	Microbial fermentation product (<i>Saccharopolyspora spinosa</i>)	Thrips, caterpillars, leafminers	Low: photolysis half-life in water <1-2 days	Low aquatic toxicity; rapidly degrades in sunlight.	27
Azadirachtin	Botanical extract (<i>Azadirachta indica</i>)	Aphids, whiteflies, beetles	Very low: degrades in water <35 h; soil ~1-2 days	Minimal aquatic toxicity; biodegradable and non-bioaccumulative	28
E8, E10-Dodecadien-1-ol	Synthetic insect pheromone (semiochemical)	Codling moth (<i>Cydia pomonella</i>)	Very low: dissipates within hours to days	No toxic effects; no accumulation in water; species-specific	29

Mitigating water pollution through green pesticides

Lower ecotoxicity: Fundamentally, owing to their precision-engineered molecular architectures, these active ingredients and their subsequent degradation products exhibit negligible ecotoxicity toward aquatic organisms. For example, the “reduced-risk” bioinsecticide spinosad shows low acute mammalian toxicity (rat oral LD₅₀ = 3,738 mg/kg in males and >5,000 mg/kg in females, EPA) and EFSA’s peer-reviewed risk assessment concluded a low risk to aquatic organisms for spinosad and its pertinent metabolites for representative greenhouse uses.³⁰ Concurrently, by eliminating environmentally deleterious solvents and surfactants during formulation, these systems significantly mitigate the risks associated with hazardous chemical runoff. For instance, Li et al. developed an aqueous unimolecular nanopesticide architecture that bypasses conventional aromatic solvents. Ecotoxicological assays on non-target zebrafish (*Danio rerio*) yielded a safety metric of 0.79 mg/L—calculated as the Index of Relative Toxicity multiplied by LC₅₀—which exceeded those of commercial counterparts, thereby confirming a substantially reduced aquatic risk profile.³¹

Reduced runoff and residues: Traditional formulations suffer from low deposition efficiency on leaf surfaces and inadequate soil binding affinity, facilitating their transport into rivers and groundwater via rainfall-induced runoff. The residue problem is exacerbated by the persistent nature of many synthetic active ingredients, which leads to the chronic contamination of global water resources. To mitigate runoff, we utilized the interfacial anchoring of biodegradable short fibers onto the papillae microstructures of the rice leaf.³² This micromechanical optimization resulted in superior washout resilience, maintaining a retention rate of up to 84% even under simulated heavy rainfall conditions. Looking forward, interface-driven micro-nano engineering will supersede adjuvant-heavy traditional formulations, leveraging material-biological synergies to minimize toxicological footprints and off-target ecological risks. Zhang et al. utilized photoresponsive gel-sol transitions within a supramolecular hydrogel to enhance pyraclostrobin deposition and stability while simultaneously reducing its ecotoxicological impact on aquatic organisms through *in situ* microencapsulation.³³ Moreover, Xiao et al. showed that forming metamitron cocrystals reduced soil leaching to ~20% of the technical active ingredient, supporting formulation-based mitigation of rainfall-driven losses.³⁴

Preventing persistent pollution: Conventional synthetic pesticides pose chronic aquatic risks due to their environmental recalcitrance, leading to persistent residues in water, sediment, and food webs. Consequently, green agrochemical innovation now prioritizes non-persistence, emphasizing molecular designs that undergo predictable abiotic or biotic transformation once their efficacy is realized.³⁵ Spirotetramat (a ketoenol insecticide) incorporates an ethyl-carbonate moiety that undergoes rapid hydrolytic cleavage, forming

spirotetramat-enol as the primary transformation product in regulatory metabolism and environmental-fate studies. Field soil dissipation trials reported fast disappearance of the parent ($DT_{50} = 0.3\text{--}1.0$ d; $DT_{90} = 1.1\text{--}3.5$ d), with parent residues falling below detection within 7–14 days after application.³⁶ In addition to structure-enabled degradability, low-toxicity and green photosensitisers can serve as a post-application lever to accelerate photolysis of surface residues after pest control is achieved. Using cauliflower as a plant-surface model, mint-leaf extract and riboflavin (vitamin B2) increased the photodegradation of deltamethrin and λ -cyhalothrin under light exposure, with the fastest removal under UV-C (254 nm), where pesticide concentrations decreased by up to 67–76% over the irradiation period.³⁷ These accelerated degradation pathways limit residual persistence, significantly reducing the potential for pesticide runoff into aquatic environments.

Integrating with water protection practices: Beyond the structural refinement of pesticides, the integration of green chemistry with advanced agronomic practices has yielded significant ecological dividends (**Figure 2**). Long-term implementation of Integrated Pest Management demonstrates that pesticide application can be reduced by approximately 95% without compromising crop yields, thereby directly curtailing the environmental mass load available for runoff and atmospheric drift.³⁸ Regulatory standards reinforce this systems approach by aligning explicit source-reduction targets with tighter effluent-quality mandates for treated wastewater. For instance, the EU Farm-to-Fork strategy aims for a 50% reduction in pesticide use by 2030, supported by CAP eco-schemes and agri-environment measures including buffer strips.³⁹ When coupled with strict discharge limits, such as BOD of 40 mg/L and COD of 120 mg/L,⁴⁰ these policies effectively incentivize the adoption of pest-control solutions designed to minimize runoff and leaching risks.

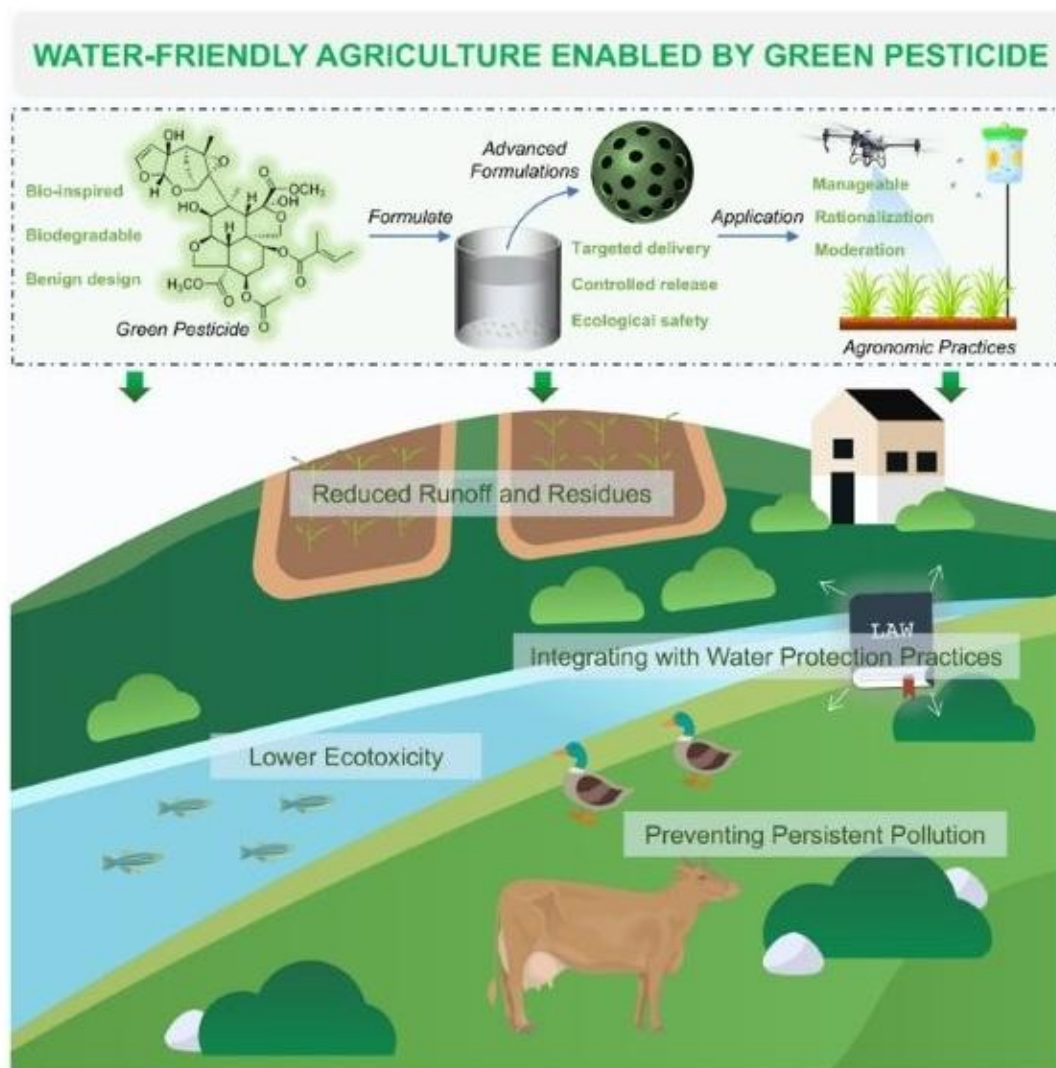


Figure 2 Rational design and targeted application of green pesticides: a paradigm shift toward water-friendly and sustainable agriculture

Conclusions

This article advocates for a green pesticide paradigm that prioritizes aquatic safety through rational molecular design and formulation engineering. This shift is vital to reconcile global food security with the right to clean water. Despite progress, adoption remains hindered by high production costs, logistical trade-offs between stability and degradability, and fragmented regulatory frameworks in developing regions. To ensure sustainable water resources, future chemical research must integrate computational and experimental tools to predict environmental fate during early-stage development. Ultimately, transitioning this conceptual framework into a global reality requires cross-sectoral collaboration—uniting technical innovation with regulatory incentives and enhanced farmer adoption to displace high-risk legacy products.

Statement on use of AI

In the preparation of this essay, Chat GPT was used to enhance the clarity and language quality of the text. Following this, the content was thoroughly reviewed and revised as necessary and the author takes full responsibility for the whole publication.

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Finalist

Quenching AI's thirst for water: engineering sustainable AI infrastructure through the chemical sciences

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Introduction

In just a few short years, Artificial Intelligence (AI) has evolved from being a niche technology to a universal tool used across industries and demographics. Data shows that 16.3% of the world's population has adopted generative AI by the second half of 2025,¹ with 88% of business organizations reporting usage in at least one core business function.² While the technology is revolutionizing the work and lifestyles of millions of people, the digital gold rush hides a physical cost: its insatiable thirst for water. Given the scarcity of this resource today, the AI phenomenon may accelerate the global water crisis, displacing access for affected communities and industries. Thus, it is vital to examine the problem through the lens of the chemical sciences to engineer a more water-efficient AI infrastructure.

Behind AI's water craze

The global scale of AI operations today is powered by the massive AI data centres scattered across the world. Inside these facilities are thousands of computer chips called graphics processing units (GPUs) which process the datasets used to train AI models. What most people do not realize is that a single high-performance chip can produce up to 700 watts of heat under full load.³ For context, that is roughly the same heat output as a small microwave oven running continuously. With data centres housing thousands of chips, expelling the heat becomes an engineering problem.

To cool down AI data centres, a two-part system is most adopted in the industry as shown in **Figure 1**. The first part uses a dielectric liquid coolant in direct contact with the GPUs via cold plates, enabling high-density thermal absorption. This process is closed-loop, which means the coolant is reused indefinitely.⁴ A heat exchanger then transfers the heat to the second stage, where water is used as it circulates to an external evaporative tower.⁵ Water is sprayed into the air, and as it evaporates, it carries the heat away since the phase change from liquid to vapor absorbs a significant amount of thermal energy. Thus, this crucial step consumes significant amounts of water.

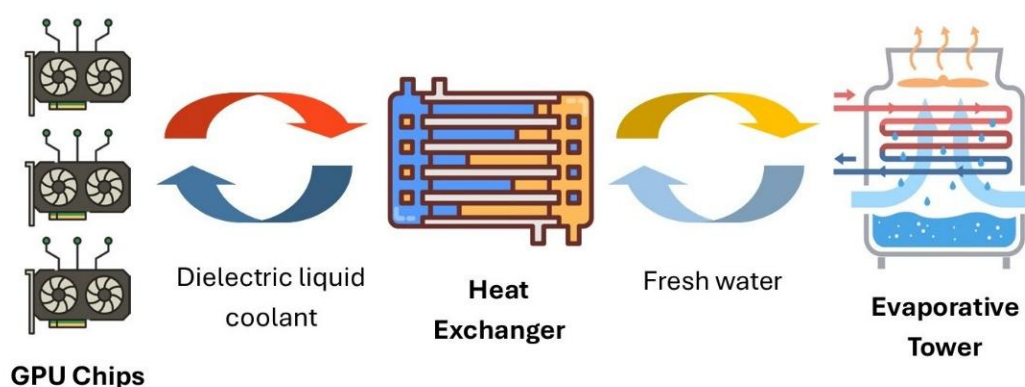


Figure 1 *Layout of a typical data centre cooling system*

A large data centre using an evaporative system uses approximately 6.81 billion litres of water annually, equivalent to the consumption of a town with up to 50,000 residents.⁶ Moreover, the global consumption of AI-specific facilities is projected to rise to 1 trillion litres annually by 2028.⁶ Because of these facts, concerns are growing about the sustainability of AI operations in terms of its heavy dependence on fresh water.

In the United States, the problem is most pronounced since it is where AI data centres are concentrated. A study by Han *et al.* revealed that US data centres may require up to 1.451 billion gallons of water per day by 2030, with costs for water infrastructure expansion reaching \$10-58 billion – which often gets passed down to consumers.⁷ On the other side of the globe, Microsoft's data centres in Jakarta, Indonesia are projected to consume 664 million litres of water by 2030,^{8,9} a provocative figure since 34.15% of the city's residents still lacked piped water access in 2023.¹⁰ Globally, AI data centres will only multiply, making it important to make their expansion sustainable in terms of water use.

Engineering sustainability in AI infrastructure

To engineer a water-efficient AI infrastructure, it is vital to assess which parts of the cooling process we can apply innovations in the field of chemical sciences. As previously discussed, water is significantly lost due to the evaporative nature of the cooling process in data centres.

To address this, there are developed interventions we can investigate. Nurrohman *et al.* created a novel mechanism to capture water vapor by letting humid air pass through a hydrophobic microporous membrane module.¹¹ Under optimal conditions, the mechanism can recover up to 75% of water vapor, a huge improvement from the 10-26% recovery of previous models. Another system is outlined in a report by the US Department of Energy which captures water droplets from cooling tower plumes through electrostatic precipitation, resulting in a significant recovery of entrained droplets.¹² While both innovations directly address the concern, they are still considered as emerging technologies.

Aside from the evaporation of water, ensuring optimal heat transfer in the system is another essential aspect to conserve water. Here, it is critical to look at the side of the second loop because fresh water is used and is more exposed to external environment, although this would also depend on the system's design since this can be a closed loop as well. Nevertheless, the combination of these two facts makes the second loop vulnerable to fouling mechanisms that can gradually degrade heat transfer efficiency.

The first fouling mechanism that should be addressed is mineral scaling, which is the buildup of hard deposits on the piping system. To counter this, the standard operation is to only reuse water up to a limit measured as Cycles of Concentration (CoC), and a portion of the mineral-heavy water must be discharged as blowdown to be replaced with fresh water. While standard systems typically operate at an inefficient 2 to 4 CoC,¹³ high-density AI data centres require much higher cycles to remain sustainable.

To increase CoC and decrease blowdown, we must address a fundamental chemical problem: how to keep minerals from building up and prevent scaling. Aside from rejecting water as blowdown, anti-scalants are also used. These are specialized additives that prevent minerals from precipitating. However, the chemicals mostly used in the industry are phosphate-based compounds that can stimulate algal growth and contribute to eutrophication in rivers and lakes.¹⁴

Studies have shown that several green alternatives such as polyaspartic acid (PASP) and polyepoxysuccinic acid (PESA) have the same performance in scale inhibition as the phosphate-based chemicals. Furthermore, these chemicals are biodegradable and have low toxicity.^{15,16} Chen *et al.* went further and formulated a mixture of tobacco stem extract and the mentioned green scale inhibitors which resulted in 100% scale inhibition and 85.7% corrosion inhibition rate.¹⁷ While the alternatives offer the same performance and fewer environmental risks, they cost more than the traditional inhibitors.

Another strategy is to recover water from the blowdown itself through electrodialysis. Li *et al.* investigated the viability of using electrodialysis to treat cooling tower blowdown water. Their study showed that the process could retain roughly 60% of the anti-scalant used in the water, allowing a substantial portion of blowdown to be recovered and reused in the cooling system. The electrodialysis process reduced capital costs by 12.6% and operating costs by 10.8% in comparison to reverse osmosis.¹⁸

Aside from scaling, biofilm growth is another fouling mechanism to look out for. This microbial phenomenon happens when organic molecules stick to the heat exchanger surface which then acts as a medium where bacteria can grow. Uncontrolled biofilm growth can significantly reduce heat transfer efficiency between the two loops since it has a low thermal conductivity – only 0.5 to 0.7 W/m.K when water has 2.0 to 2.5 W/m.K.^{19,20}

Conventional biocides pose environmental risks which necessitates the shift to alternative methods of controlling biofilm growth. One such method is the use of biofiltration to suppress biofouling. Meesters *et al.* developed a biofilter that was designed to remove assimilable organic carbon (AOC), an organic material used by bacteria for growth, which significantly reduced bacterial growth and biofilm formation.²¹ Another approach is to coat the piping system itself with a hydrophobic nano-silica material to prevent bacteria from anchoring in pipe surfaces.²² Both strategies are passive in nature, unlike the use of chemicals, but would require a significant initial investment as they are integrated into the cooling infrastructure.

Conclusions

As discussed, there is a plethora of innovations in the chemical sciences that address the concern of massive water use in data centres with promising results. At this stage, the question is no longer whether solutions exist, but how to effectively implement them.

For a long time, only power usage has been the focus of inquiry in the case of AI data centres with water considerations treated as an afterthought, and this must change. It is time for concerned countries to mandate standardized reporting of Water Usage Effectiveness (WUE), which is a key performance metric used to measure the efficiency of water use in data centres. This enables a mechanism for companies to be accountable for their water use and be transparent to concerned communities and local industries. Aside from this, the use of biodegradable scale inhibitors, biocides, and water-saving infrastructures must be supported through tax incentives or subsidies to enable widespread use in the industry. Lastly, universities and research institutes are critical for the advancement of next-generation cooling and water-recovery technologies, which should be supported by both the AI industry and governments.

As it stands today, AI will only expand in the years ahead, placing increasing pressure on our already limited freshwater resources. It will require collective effort to quench its insatiable thirst for water. By aligning innovations in chemical sciences with responsible stewardship, we can engineer the next generation of water-efficient data centres and ensure sustainable water access for both community and industrial needs.

Statement on use of AI

Use of Artificial Intelligence (AI): AI was used in the preparation of this essay for checking grammar and punctuation issues, refining the clarity of texts, and ensuring the essay's adherence to the Royal Society of Chemistry (RSC) formatting guidelines. The author has reviewed and validated all AI-generated suggestions and assumes full responsibility for the submitted essay.

The Figure used in the essay was created using Microsoft Publisher software and the graphics were sourced from open-license repositories.

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Finalist

Cleaning up, improving access and reducing use: the three-pronged approach to ensure sustainable access to clean water

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The Royal Society of Chemistry's magazine, Chemistry World



In 2025, one in four people worldwide lacked access to clean water – around 2 billion people.¹ Clean water is safe for its intended use – such as drinking, bathing, agriculture or industrial processes – and is free from harmful levels of contaminants.² Growing populations, extreme weather conditions and contamination from natural and industrial pollutants are continuing to reduce the amount of clean water available for such uses.^{3,4}

There needs to be a shift in how society obtains, uses and recycles water to ensure that current and future global populations can access the required quantities of this invaluable resource. Equally, prices of clean water need to be kept low, ideally by incorporating new technologies into existing infrastructure. While some of the opportunities to do so lie in other disciplines such as politics, engineering, ecology and computer science, the chemical sciences are still fundamental to achieve a sustainable access to clean water.

This essay focuses on three areas that could help address this goal: cleaning up current water sources; increasing access to other water sources; and reducing water consumption.

Cleaning up

Ensuring access to clean water requires ways to decontaminate supplies. Contaminants may include heavy metals, organic compounds, pesticides, fertilisers, microplastics, and radioactive waste, which may be from a natural or industrial source.⁵⁻¹⁰

For example, per- and polyfluoroalkyl substances (PFAS) are a class of organic contaminants that are widely spread in the environment and humans.¹¹ Exposure to high levels of such compounds can cause infertility, cancer, and disrupt hormone regulation.¹² These materials are used in applications such as non-stick pans, firefighting foams and sealants. However, these water-soluble compounds are notoriously difficult to break down and remove using standard wastewater treatment methods, owing to their strong carbon–fluorine bonds.¹¹ Sonolysis – a method that uses ultrasound waves to break down molecules – has been shown to break down PFAS into carbon dioxide, carbon monoxide and fluoride, without the need for any catalysts or other chemicals.^{13,14} Industrial-scale trials have been conducted with perfluorooctane sulfonate at a 91-litre scale.¹⁵

Using ultraviolet (UV) radiation, chlorination and filtration can sterilise and clean up water sources. However, these methods can struggle to break down persistent biological and organic pollutants, including bacteria, viruses, dyes and pharmaceuticals.¹⁶ Cold plasma technology could be an alternative. Passing gaseous species through an electric field can generate short- and long-lived reactive species, such as hydroxy radicals, hydrogen peroxide, ozone and superoxide. These are then able to degrade pollutants or inactivate biological species.¹⁶ Cold plasma exists close to room temperature and pressure, meaning its generation requires less energy than typical thermal plasma. This decontamination strategy therefore requires no additional chemicals (like chlorination) and offers options to use intermittent, renewable energy sources.

Developing more selective membranes will also be necessary to remove very low concentrations of contaminants. For example, membranes with angstrom-sized ion channels could separate metal ions and other contaminants from water sources with better selectivity and at lower concentrations.^{17,18}

Increasing access

Clean water is a scarce resource. Currently, only 3% of water on Earth is freshwater, with two thirds of that trapped in glaciers or ice caps.¹⁹ Unlocking a greater proportion of all global water sources is crucial to meet future demands.

Capturing water from the atmosphere offers one way to do so, particularly in regions with little annual rainfall. This would ensure access to a steady supply of clean water. One strategy is to use metal-organic frameworks (MOFs), where these material's high porosity and tuneable properties makes them suitable to capture and release water from air.²⁰⁻²³ One study found that a zirconium-based MOF (MOF-801) was able to capture water from the atmosphere at humidity levels as low as 20%, similar to that found in deserts.²⁰

Researchers of the study have founded the start-up Atoco to commercialise the material, claiming that a 20-foot container powered by solar energy can generate around 1000 litres of freshwater per day.^{24,25}

Reverse osmosis (RO), in which a supplied pressure pushes water against an osmotic barrier through a membrane, is another desirable strategy. Many desalination plants use RO in order to tap into the ocean's water supply by removing salt, typically sodium chloride (NaCl). However, RO is energy intensive – RO desalination plants use around 2.5 to 6 kWh to produce one metre cubed of water, with some estimates suggest that by 2050, emissions from the desalination is expected to reach 0.4 billion tonnes of CO₂.^{26,27} Solar-powered RO desalination could offer a way to reduce the associated emissions, as well as store excess energy with battery technology to ensure a continuous supply of freshwater.²⁸

Removing salt from seawater also generates brine, a concentrated salt solution, which is often released back into water systems, impacting local wildlife. One way to overcome this issue is by using electrochemistry to convert the brine into sodium hydroxide – which can be used in the desalination plant itself – and hydrogen chloride, a valuable chemical.²⁹

Reducing use

Even if new chemical technologies or otherwise can clean up and increase access to untapped water sources, effectively controlling available water is necessary to meet future demands. Looking inwards to the chemical sciences, this sector can limit and reduce its water usage in several ways. For example, exchanging a typical water condenser for an air condenser, ensuring that solvent streams are correctly separated to allow wastewater to be recycled, or using chillers to cool solvents and samples are all things that working chemists can do to reduce their individual water usage.³⁰

Solvent-free synthesis, which eliminates the need for aqueous solvents or water to produce organic solvents, offers another way to reduce use. Mechanochemistry – where reactants are ground or crushed together, often through ball milling – could be a way to do this.^{31,32}

Other potential ways to limit the need for solvents include: Microwave-assisted synthesis, solid-state reactions, and sonolysis (without solvent).³³⁻³⁵

Producing reagents at source would also reduce the need for solvent. Chemical suppliers often concentrate reagents, with consumers then re-diluting accordingly, wasting both water and energy. To overcome this, one strategy uses a palladium-based catalyst to produce hydrogen peroxide in-situ from dilute concentrations of hydrogen and oxygen gas (at concentrations that can be made from electrochemical water-splitting reactions) at levels required for most reactions.³⁶

Financial sustainability

Many of these technologies offer a way to clean up available water supplies, increase access or reduce usage. However, the use of expensive metals, specialised fabrications and their newness to market can make these techniques inherently costly. This can deter industries and communities from adopting these strategies.

Regions that are facing more extreme weather events as a result of climate change are also often less able to afford to implement strategies that address water scarcity issues. Making strategies more financially viable, potentially even turning a profit, may incentivise such communities to adopt some of the methods discussed earlier.

Turning waste products from water supplies offers one way to overcome this issue. One study developed an electrochemical sensor from electronic waste to detect mercury, cadmium and lead levels at concentrations below the World Health Organisation (WHO) recommended levels.³⁷ Designing highly accurate sensors will also help ensure that contaminants can be detected, even at low levels.

Another strategy used sodium hydroxide to turn wastewater treatment plant sludge containing arsenic salts into metallic arsenic nanoparticles.³⁸ Arsenic is a toxic element that naturally contaminates water sources. The metal is highly sought after for electronic components, reaching up to \$1000/kg; in 2022, the US classified it as a critical raw material.³⁸ This strategy would likely incentivise poorer communities to decontaminate water sources. Other similar examples include upcycling cadmium-, nickel-, and microplastic-contaminated waste streams to produce valuable commodities.³⁹⁻⁴¹

Conclusions

The chemical sciences will undoubtedly help reach the UN's development goal of ensuring sustainable access to clean water for all. This will occur by: cleaning up our current supplies of freshwater; increasing access to other water sources, such as the sea and water in the atmosphere; and reducing water usage to conserve limited supplies.

However, this goal will not be achieved by the chemical sciences alone – other sectors will too be critical. Engineering solutions are needed to improve water transport systems with fewer leaks, create water storage systems, and help scale chemical technologies. Governments will also play a crucial role, primarily in helping to change how consumers use available water, raise awareness of contaminants in water streams and help prevent companies from releasing untreated wastewater.

Statement on use of AI

No artificial intelligence (AI) was used in the preparation of this essay.

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Finalist

From pollution to purity: metal-organic frameworks enable sustainable clean water access

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Structural advantages of MOFs: more than just “high surface area”

Metal-Organic Frameworks (MOFs), which were awarded the 2025 Nobel Prize in Chemistry, are formed by the self-assembly of metal nodes and organic linkers via coordination bonds, creating three-dimensional periodic networks.¹ Their modular construction allows precise control over topology, pore size, and chemical environment at the molecular level.² However, what truly distinguishes MOFs from traditional porous materials is their “programmability”—we can pre-design pore polarity, hydrophobicity, and functional group arrangements much like building with Legos. This capability means that MOFs can be “tailor-made” for specific classes of pollutants (e.g., positively charged heavy metals or aromatic organics). In water purification, the core advantages of MOFs extend far beyond high surface area: pore sizes can be continuously tuned from sub-nanometer to several nanometers, unifying size exclusion and selective enrichment; surfaces can be post-synthetically modified with $-\text{NH}_2$, $-\text{SH}$, $-\text{COOH}$, and other groups, upgrading physical adsorption to chemical capture.³ More notably, MOFs simultaneously possess multifunctional potential for adsorption, catalysis, and sensing—a capability that is difficult to achieve with activated carbon or zeolites. The capture of pollutants by MOFs does not rely on a single physical adsorption mechanism, but is achieved through the synergy of multiple chemical mechanisms (**Figure 1**). As shown in the left half of Figure 1, the removal of heavy metal ions primarily depends on the triple mechanisms of coordination, ion exchange, and electrostatic adsorption; while the right half illustrates the efficient enrichment of organic pollutants through π - π stacking, hydrophobic interactions, and hydrogen bonding networks. This “multi-mechanism synergy” is precisely the core advantage that distinguishes MOFs from traditional adsorbents—they do not passively “hold” pollutants, but actively “capture” them.

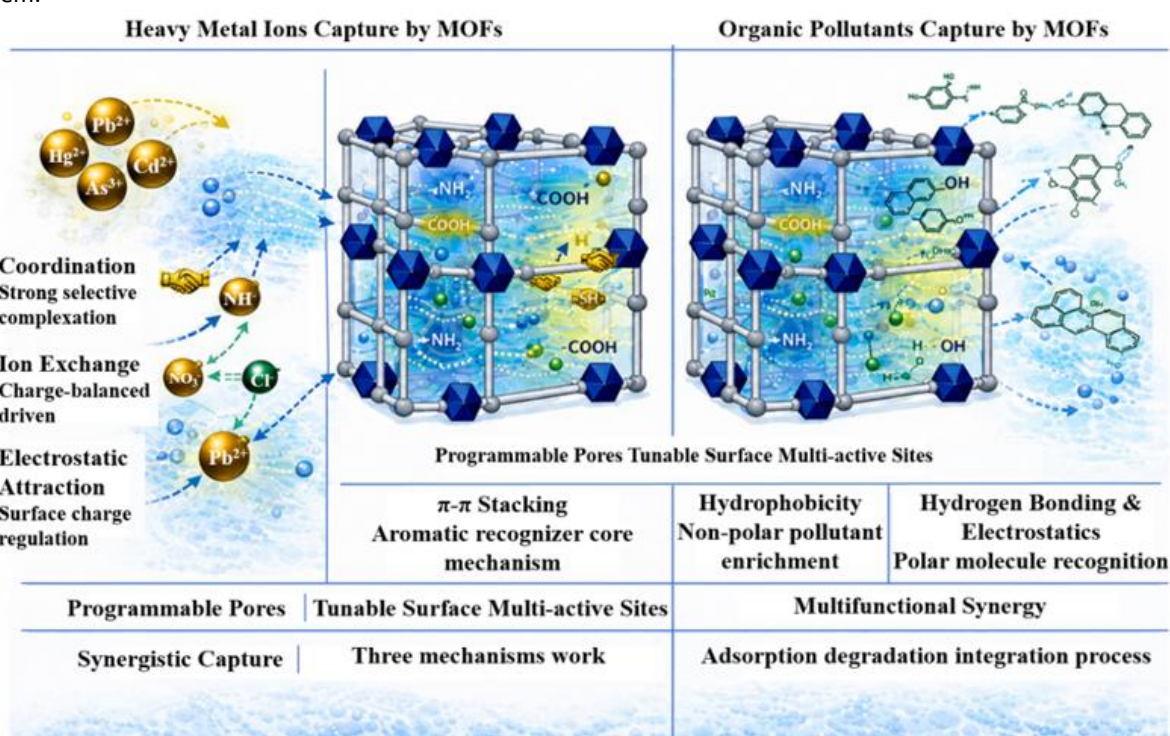


Figure 1 Schematic diagram of the multiple capture mechanisms of metal-organic frameworks (MOFs) for heavy metal ions and organic pollutants.

Capturing heavy metals: from coordination chemistry to engineering challenges

Heavy metal ions (Pb^{2+} , Hg^{2+} , Cd^{2+} , Cr^{6+} , As^{3+} , etc.) exhibit irreversible neurotoxic and nephrotoxic effects even at microgram-per-litre levels.⁴ Traditional methods such as ion exchange, chemical precipitation, or membrane filtration generally suffer from poor selectivity, high operating costs, or secondary sludge when treating complex water matrices. The intervention of MOFs essentially brings the precision of coordination chemistry into water treatment.

MOFs adsorption of heavy metals relies primarily on three mechanisms, which often act synergistically. Coordination is the most central pathway: unsaturated metal sites or N/S/O-containing groups on linkers form stable complexes with heavy metal ions. Ion exchange occurs within the pores of some MOFs, where counterions (e.g., NO_3^- , Cl^-) on the framework can be displaced by heavy metal cations. Electrostatic adsorption further enhances enrichment efficiency through surface charge modulation. While these three mechanisms sound straightforward, the real challenge lies in making them work simultaneously and efficiently in real water bodies.

Illustrative examples demonstrate progress. UiO-66- NH_2 achieves adsorption capacities of several hundred mg/g for Cr(VI), attributed to the strong coordination ability of amino groups.⁵ Sulfur-functionalized ZIF-8-SH exhibits selectivity for Hg^{2+} that is more than two orders of magnitude higher than for other coexisting ions—owing to the extremely strong affinity between Hg^{2+} and thiol groups.⁶ MOF@cellulose composites, which address the engineering pain point of difficult separation and recovery of powdered MOFs, have been validated in industrial wastewater.⁷ However, water stability remains prominent: some MOFs undergo framework collapse after prolonged immersion in water. Regeneration typically requires strong acids or strong complexing agents, which can damage the structure. Selectivity enhancement remains an unresolved challenge—competitive adsorption from coexisting ions (e.g., Ca^{2+} , Mg^{2+}) cannot be ignored. Future breakthrough directions may lie in designing MOFs with dual selectivity combining size exclusion and specific coordination, or developing smart materials that can be regenerated under mild conditions.

Organic pollutants: the marriage of π - π stacking and catalysis

The list of organic pollutants is long: synthetic dyes, pesticide residues, antibiotics, pharmaceutical byproducts, endocrine disruptors, and more. Most possess stable aromatic ring structures, are resistant to biodegradation, and some are ecotoxic. The adsorption mechanisms of MOFs toward such pollutants are both familiar and unique.⁸ π - π stacking is a key interaction between aromatic pollutants and MOF organic linkers—when the linker contains aromatic rings, it can stack with the benzene rings of target molecules, significantly enhancing affinity. Hydrophobic interactions, by tuning pore hydrophobicity, enable selective enrichment of nonpolar organics (e.g., polycyclic aromatic hydrocarbons, certain pesticides). Hydrogen bonding and electrostatic interactions are also important for polar molecules (e.g., dyes).

MIL-101(Cr) exhibits adsorption capacities for methylene blue exceeding 1000 mg/g, far higher than activated carbon.⁹ ZIF-8, with its suitable pore size and hydrophobic environment, successfully achieves efficient capture of triazole pesticides.¹⁰ But the truly exciting development is the combination of MOFs with photocatalysis—MOF/ TiO_2 composites can simultaneously adsorb pollutants and, using photocatalysis,¹¹ generate reactive oxygen species to degrade organic molecules in situ into CO_2 and H_2O . This upgrades “adsorption” to an integrated “adsorption-degradation” system, avoiding subsequent solid waste disposal.

Of course, challenges remain equally severe. Natural organic matter (e.g., humic acid) and multiple coexisting organics can significantly impair adsorption efficiency for target pollutants. Large organic molecules may block micropores, leading to rapid capacity loss. How to dispose of MOFs after adsorption saturation? If they are merely landfilled as solid waste, that transfers pollution rather than solving it. A more promising direction involves recovering valuable resources (e.g., dye intermediates, drug precursors) from adsorbed organics, or achieving synergistic regeneration of MOFs and adsorbates. This requires collaboration between chemistry and separation engineering.

Scaling up: from powder to module

No matter how impressive MOFs performance is in the lab, without large-scale production and fabrication into practical devices, it remains theoretical.¹² Traditional solvothermal methods yield high-quality crystals but involve long reaction times, high energy consumption, and reliance on organic solvents—all costly on an industrial scale. Green synthesis routes (aqueous-phase synthesis, room-temperature synthesis, microwave-assisted, mechanochemical) are changing this landscape. Companies such as BASF and MOF Technologies have achieved ton-scale production, paving the way for water treatment applications.

But synthesis is only the first step. Powdered MOFs perform well in batch adsorption but are difficult to separate from liquids. Shaped bodies—MOF beads, MOF membranes, MOF@sponges—become a necessity.¹³ Among these, mixed-matrix membranes (embedding MOF particles in a polymer matrix)¹⁴ offer both high

selectivity and continuous separation capability, showing great promise. Combining MOFs with natural polymers such as cellulose and chitosan not only improves mechanical stability but also imparts biodegradability, reducing environmental footprint.

Life cycle assessment (LCA) and techno-economic analysis tell us a straightforward truth: the initial cost of MOFs is indeed higher than that of activated carbon, but their higher adsorption capacity and longer cycle life can achieve overall cost advantages over long-term operation.¹⁵ Therefore, improving reusability is not just a performance optimization issue but the core of economic feasibility. The transition from powder to module ultimately requires realization in practically operable water treatment devices. Currently, the engineering application of MOFs is advancing along two main technical routes: fixed-bed adsorption columns and fixed-bed catalytic reactors (Figure 2). Although both fall under the fixed-bed configuration, their functional roles are distinctly different—the former centres on physical adsorption and is suitable for resource recovery from high-concentration wastewater; the latter, by coupling with advanced oxidation processes, achieves in-situ mineralization of persistent pollutants at low concentrations.

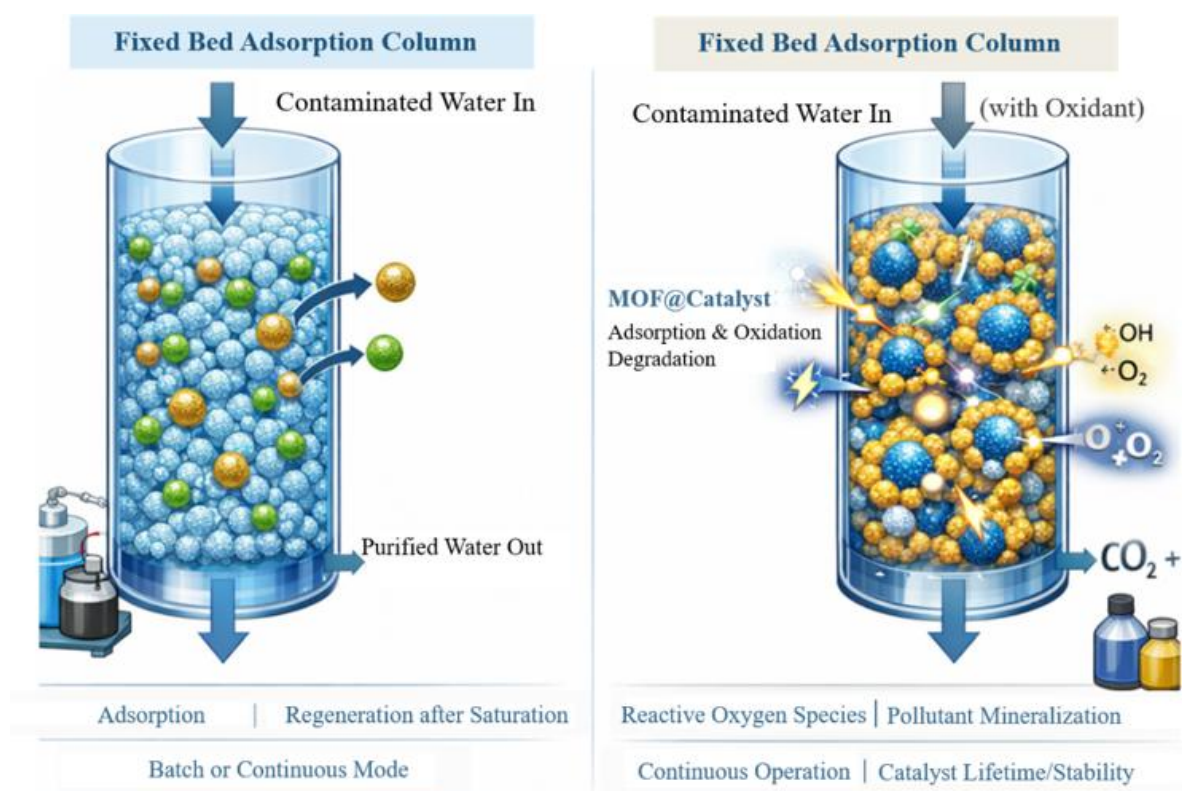


Figure 2 Two core application configurations of metal-organic frameworks (MOFs) in water purification: fixed-bed adsorption column and fixed-bed catalytic reactor.

It is worth emphasizing that the progression from adsorption columns to catalytic reactors represents not merely a functional enhancement, but rather a paradigm shift in MOFs-based water treatment technology—from “pollutant enrichment” to “pollutant destruction.” Research by Professor Wang Chongchen’s team has demonstrated that immobilizing MOF catalysts on expanded perlite and packing them into fixed-bed reactors enables stable operation under continuous-flow conditions for over 30 days, maintaining removal efficiencies above 90% for various organic pollutants.¹⁶ This advancement indicates that MOFs are no longer confined to shining only in laboratory beakers; they are proving their value in real-world water treatment scenarios.

Beyond chemistry: social synergy and policy support

Technology is never just technology. For MOFs-based water purification devices to truly reach communities, factories, and rural areas, public awareness is essential. Most people know nothing about “metal-organic frameworks”—which is normal. But through science education and demonstration projects, we can help the public understand that this material can provide them with cleaner water. Community-level pilot projects are key to bridging the gap between the laboratory and reality.

Interdisciplinary synergy is another indispensable dimension (**Figure 3**). Chemists design more stable and selective MOFs; materials scientists address shaping and interfacial issues; environmental engineers conduct long-term operational evaluations in real water bodies; mathematicians provide data support for process optimization through adsorption kinetic modelling and cost prediction. No single discipline can accomplish the entire task alone.

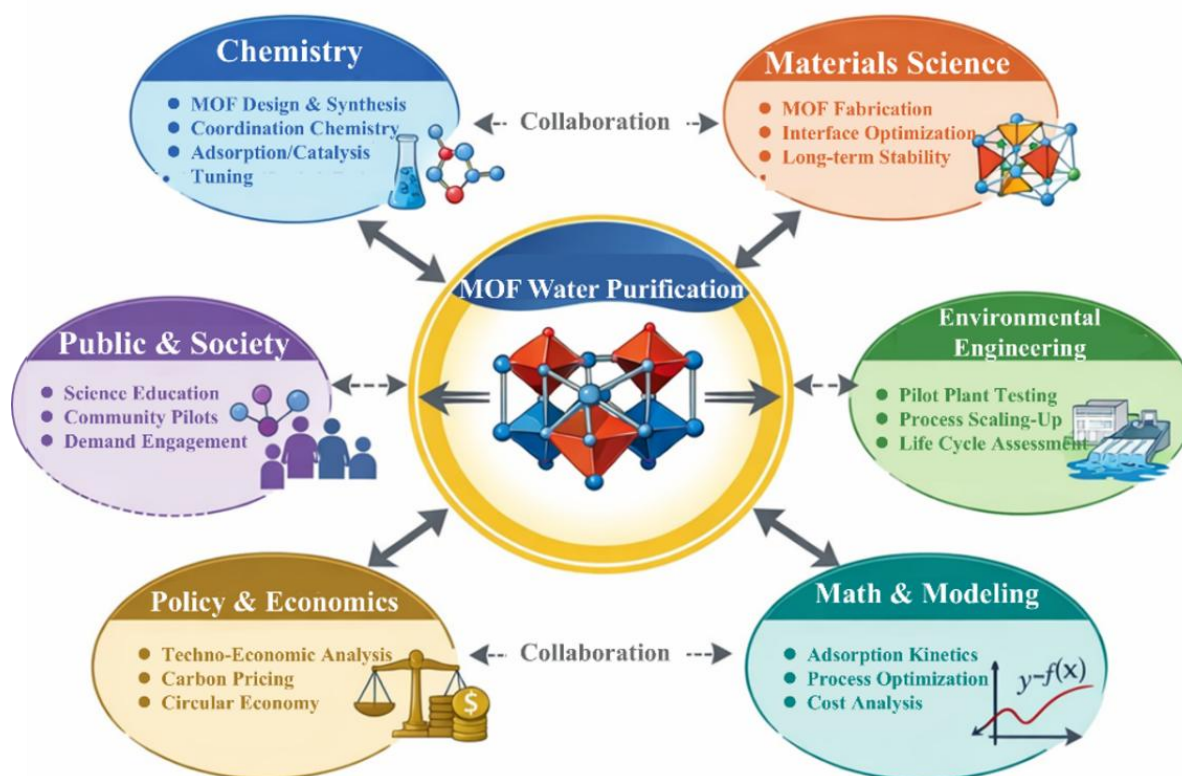


Figure 2 Interdisciplinary synergy network for MOFs-based water purification technologies.

Outlook: how far do we still have to go?

The potential of MOFs for clean water is beyond question. But from laboratory to practical application, water stability, regeneration efficiency, selectivity enhancement, and cost control—each is a tough challenge. Three directions deserve the most attention: firstly, developing novel MOFs with ultra-high water stability and facile regeneration; secondly, promoting the integration of MOF shaping technologies with existing water treatment processes to achieve the transition from powder to membranes/beads; thirdly, establishing a complete chain from materials research to engineering validation to social deployment, which requires policymakers to provide funding support and regulatory incentives.

Chemical science, through advanced materials such as MOFs, provides key technological support for the goal of “clean water for all.” But successful implementation is never solely about chemistry. It requires the joint efforts of materials scientists, environmental engineers, economists, policymakers, and every ordinary person. How far are we from that day? The answer depends on our actions today.

Statement on use of AI

AI was used to polish the language and enhance the visual quality of some images in this essay. They were not used to generate scientific content, analyse data or draw conclusions.

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Finalist

Democratizing the drop: how paper chemistry bridges the global water gap

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Introduction

Access to clean water is not merely a logistical challenge of infrastructure, it is a fundamental issue of chemical identification. While the world focuses on large-scale filtration, millions remain exposed to invisible killers such as heavy metals like lead and arsenic, or microbial pathogens, simply because they lack the means to detect them.¹ Current gold-standard techniques, such as inductively coupled plasma mass spectrometry (ICP-MS), are confined to centralized urban laboratories, requiring stable electricity and highly trained personnel. For a rural community or a disaster-stricken zone, this creates a fatal information gap.² The chemical sciences must therefore pivot from increasing analytical precision to increasing analytical accessibility. This essay explores how paper-based chemical sensors, or microfluidic paper-based analytical devices (μ PADs), can democratize water safety, providing a sustainable, low-cost, and power-free solution for all.

The chemistry of microfluidic paper-based analytical devices

μ PADs represent a paradigm shift in analytical chemistry toward functional simplicity. Unlike traditional lab-on-a-chip systems made of glass or silicon, μ PADs utilize the natural, porous network of cellulose fibres. The chemical principle at play is capillary action, which allows an aqueous sample to wick through the paper's matrix without the need for external pumps or electrical power. The mechanism is shown in **Figure 1**. This capillary-driven flow is driven by the high surface energy of cellulose, where hydroxyl groups on the fibre surface form hydrogen bonds with water molecules, effectively pulling the liquid through the device.

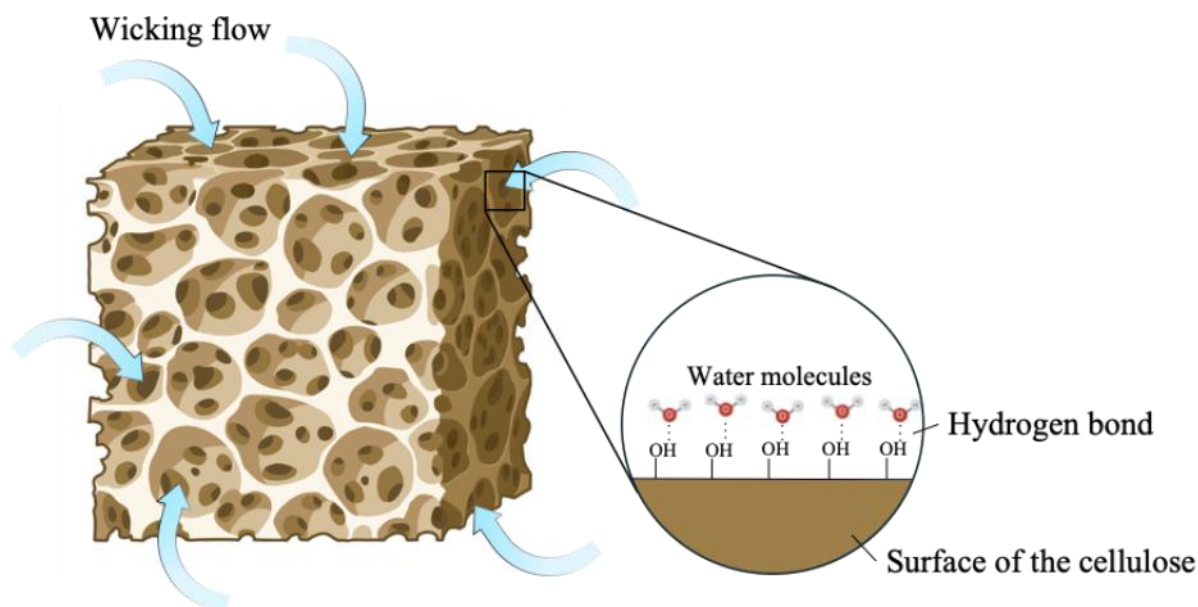


Figure 1 Microscopic interaction between cellulose fibers and water molecules. The porous matrix of the paper substrate facilitates wicking flow through capillary action. The magnifying inset illustrates the high surface energy of cellulose, where surface hydroxyl (-OH) groups form hydrogen bonds with water molecules, providing the driving force for passive fluid transport.

Note: The figure was partially created with BioRender.com under a regular publication license.

To transform a simple piece of paper into a sophisticated diagnostic tool, the substrate must undergo chemical patterning.³ By using hydrophobic agents, such as wax, “walls” can be created within the paper to

define precise microfluidic channels as shown in **Figure 2**.³ These hydrophobic barriers direct the flow of the water toward specific reaction zones. Furthermore, the high surface-area-to-volume ratio of the porous cellulose provides an ideal environment for the immobilization of chemical reagents. This enables multiple chemical tests to be performed simultaneously on a single, postage-stamp sized device as shown in **Figure 3**. This combination of low-cost material science and energy-neutral fluid control is the cornerstone of sustainability. It allows water monitoring to function in off-grid areas without existing infrastructure, effectively brings laboratory-grade precision to the remote communities globally.

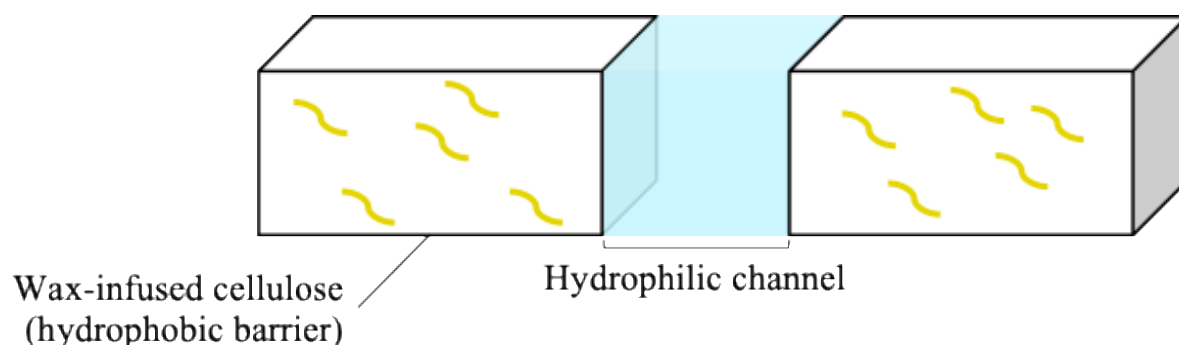


Figure 2 3D cross-sectional schematic of a paper-based channel. The lateral boundaries consist of cellulose fibres fully encapsulated by hydrophobic wax, creating robust barriers that confine the liquid. The central region remains unpatterned, allowing the aqueous sample to transport spontaneously via capillary action through the porous fibre network

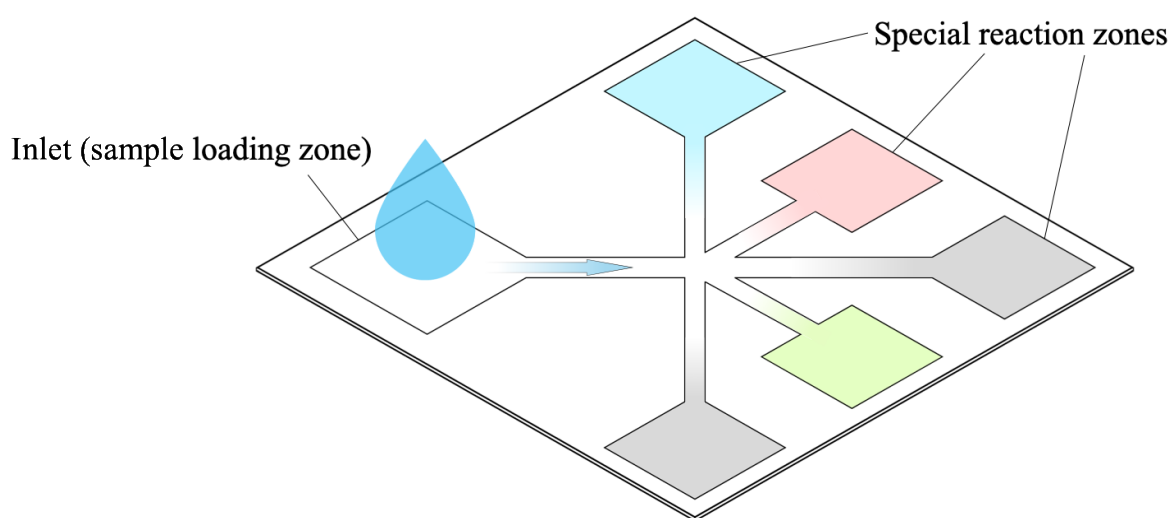


Figure 3 Schematic of a multi-channel μ PAD for parallel water quality monitoring. The inlet allows for the introduction of a single aqueous sample (water), which is then distributed via capillary action through patterned channels to multiple special reaction zones. The channels are created by printing or infusing wax into paper fibres. Each zone can be functionalized with specific chemical reagents to detect different contaminants simultaneously, enabling comprehensive analysis on a single postage-stamp sized device.

Molecular recognition and signal amplification

To transform a patterned paper substrate into a functional sensor, the material must be functionalized with highly specific molecular recognition elements. In this situation, nucleic acid aptamers serve as the critical recognition units. These are single-stranded deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) sequences, selected *in vitro* through the systematic evolution of ligands by exponential enrichment (SELEX) process to bind specific targets such as Pb^{2+} or organic pollutants with high affinity.⁴ From a sustainability perspective, aptamers offer significant advantages over traditional protein-based antibodies. Because they are chemically synthesized,

aptamers exhibit superior thermal stability and a long shelf-life without the requirement for a cold chain. This structural robustness ensures that the sensors remain reliable in the fluctuating temperatures often encountered during field testing in remote or tropical regions. The detection of trace contaminants requires a measurable output signal, which is achieved through the integration of nanozymes. These inorganic nanomaterials, such as gold nanoparticles or metal-organic frameworks (MOFs), possess intrinsic enzyme-like catalytic activities.⁵ When the target pollutant binds to the aptamer, it modulates the nanozyme's ability to catalyse a chromogenic reaction. For instance, the oxidation of a colourless substrate into a vibrant blue product allows for a visual readout that can be interpreted or quantified using a smartphone camera. This dual-layer chemical design, combining the selectivity of aptamers with the catalytic power of nanozymes, effectively bypasses the limitations of natural biological components. It creates a sensing system that is both precise and sufficiently rugged for universal application, fulfilling the chemical sciences' objective of providing clean water safety for all needs.

Realism and challenges

While the chemical principles of paper-based sensors are robust, their application in diverse environmental conditions presents specific challenges. The inherent porosity of cellulose, which facilitates capillary flow, also makes the substrate sensitive to ambient humidity. High moisture levels can alter the wicking speed of the sample, potentially leading to inconsistent reaction times and signal variability. To mitigate this, the chemical sciences offer solutions through surface modification. By applying precise concentrations of hydrophobic polymers or silane-based coatings, chemists can regulate the evaporation rate and stabilize the fluidic dynamics within the paper channels, ensuring reproducible results regardless of the external climate.

Another significant barrier is the semi-quantitative nature of colorimetric readouts. Visual interpretation of colour intensity is subjective and can be influenced by lighting conditions at the source. To achieve laboratory-grade precision in the field, the integration of digital image colorimetry (DIC) is essential. Using a smartphone camera as a portable densitometer, the colour intensity on the paper sensor can be converted into a digital signal. This signal is then processed through an algorithmic calibration curve to provide an accurate concentration of the target pollutant.

This integration of material chemistry and digital technology addresses the requirement for both reliability and accessibility. By acknowledging and engineering solutions for these practical barriers, the chemical sciences demonstrate a realistic pathway toward universal water safety, ensuring that decentralized monitoring can meet the rigorous standards necessary for public health protection.

Science, society, and policy: a decentralized future

The transition from laboratory-based testing to paper-based chemical sensors necessitates a parallel shift in public health policy. To ensure sustainable access to clean water for all, chemical innovation must be integrated into a broader framework of citizen science and digital surveillance.⁶ By empowering local communities to conduct their own water quality assessments, we can generate high-resolution, geo-tagged datasets that were previously unattainable through centralized monitoring.

For such a decentralized system to succeed, policymakers must establish regulatory standards that recognize the validity of field-ready chemical diagnostics. This involves creating digital platforms where chemical sensor data can be uploaded and verified in real-time, allowing for rapid intervention by health authorities when contamination "hotspots" are identified. In this model, the chemical sciences act as a catalyst for social equity, ensuring that even the most marginalized populations have the tools to demand and verify their right to safe water. The role of the chemist thus extends beyond the bench, serving as a bridge between molecular engineering and the fundamental needs of global society.

Conclusions

Ensuring sustainable access to clean water is one of the most pressing challenges of the twenty-first century. As demonstrated, the chemical sciences provide a versatile toolkit to address this crisis through the development of paper-based chemical sensors. By leveraging the unique properties of cellulose, the specificity of nucleic acid aptamers, and the catalytic power of nanozymes, we can bypass the infrastructure barriers that currently restrict water safety to developed urban centres. While technical challenges regarding environmental stability and data quantification remain, the integration of material chemistry with digital technology offers a realistic and scalable solution. Ultimately, as we democratize the power of chemical analysis, we do more than just test water. We

bridge the global gap in health equity. By ensuring that every drop is safe and every community is empowered, we fulfil the essential promise of a sustainable and accessible reality for our entire global community.

Statement on use of AI

AI was used in the preparation of this essay for improving the grammar and clarity of the pre-written text. The initial writing, conceptual framework, logical arguments, and the creation of all supporting figures and tables were performed entirely by the author. The author remains fully responsible for the scientific integrity and original content of this submission.

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Finalist

From Contaminants to Clean Drops: How Chemical Sciences Can Secure Sustainable Water for All

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Introduction

Clean water serves as an essential resource that sustains ecosystem balance, agricultural output, power production and public wellness. Approximately 2 billion people around the world currently face a drinking water access crisis because they lack properly managed drinking water systems, and water availability has become worse due to pollution, urban development and rising population numbers and climate change impacts. ¹ The global water crisis exists because it contains both chemical and hydrological elements. Water quality depends on the presence of chemical pollutants, including pathogens, heavy metals, pharmaceutical drugs, pesticides, and new pollutants such as microplastics. ²

Chemical sciences provide essential tools that enable scientists to study water systems through observation and modification, and play a fundamental role in sustainable water management through advanced filtration methods and the detection of waterborne pollutants at molecular dimensions. ³ The existing water treatment procedures need to develop cost-effective solutions that protect the environment and use less energy to achieve their mission of providing people with permanent access to safe drinking water. The field of chemical sciences uses its various components, which include green chemistry, advanced materials development and analytical monitoring together with circular water management to create a system that delivers water access for everyone in an equitable manner while creating sustainable water resources. ⁴

Understanding the chemistry of water contamination

Water contamination originates from various human activities that include agriculture, pharmaceutical production, industrial discharges and improper waste management. Heavy metals such as arsenic, lead and mercury, phosphate and nitrate, together with persistent organic pollutants, represent chemical contaminants that build up in water bodies and create dangers for both ecosystems and human health. ⁵

Advanced analytical chemistry allows scientists to detect pollutants at extremely low concentrations. Early pollution detection is achieved through methods that include mass spectrometry, electrochemical sensors and high-performance liquid chromatography usage before dangerous chemical levels emerge. ⁶ Real-time monitoring technologies hold special importance for developing countries because their contamination problems remain hidden until people start suffering health effects. ⁷

Current analytical chemistry practices enable scientists to achieve better environmental sustainability than their past methods. The combination of microfluidic devices and miniature sensors with solvent-free sample-preparation methods establishes a system that prevents hazardous waste creation while decreasing energy consumption and operational expenses. The methods enable continuous monitoring of water quality in areas that lack resources or have remote locations. ⁸

The transition from conventional wastewater treatment to modern advanced technologies has brought about a significant improvement in achieving sustainable and efficient water management. The traditional methods, which include coagulation, conventional sedimentation and chlorination, concentrate on bulk pollutants, but they fail to eliminate emerging contaminants while creating dangerous byproducts. The advanced techniques, which include membrane filtration, sophisticated oxidation procedures and electrochemical treatments, enable precise removal of trace contaminants through their operation with reduced chemical demands.

Advanced materials for sustainable water purification

Chemical sciences provide their most significant advantage through their ability to create materials that effectively purify water. Water treatment technologies now use nanostructured materials, advanced membranes and catalytic surfaces as their fundamental components. ⁹

Bacteria, organic pollutants, and dissolved salts are eliminated from water using membrane filtering techniques, including reverse osmosis and nanofiltration. These technologies find extensive application in

desalination plants and municipal water treatment facilities. The conventional membranes show two main problems: they experience membrane fouling, incur high energy expenses, and their maintenance costs remain extremely high. The recent progress in the materials chemistry field brings solutions to existing materials problems through graphene-based membranes, biomimetic aquaporin channels, and antifouling polymer coatings that enhance permeability while decreasing energy requirements.¹⁰

Adsorptive materials, which include metal-organic frameworks and biochar-derived carbon materials, demonstrate their ability to selectively remove pollutants through their capacity to extract heavy metals and pharmaceutical compounds. The materials can be designed at their molecular structure to capture particular contaminants, which allows for effective water treatment even when pollutants exist at minimal levels.¹¹

The research focuses on photocatalytic materials, which include titanium dioxide and other semiconductor catalysts, as a potential solution for solar-powered organic pollutant degradation. Photocatalysis uses sunlight as its power source to provide an eco-friendly method for eliminating long-lasting contaminants while avoiding the creation of toxic waste materials.¹²

Membrane bioreactor technology, a modern approach to wastewater treatment, offers multiple advantages over conventional activated sludge systems because it achieves higher sludge retention and better biomass retention, resulting in more effective pollutant removal and better microplastic particle removal from their wastewater streams.¹³

Green chemistry approaches to water treatment

Traditional water treatment processes use chemical reagents for their operations, which create secondary pollution problems because of their chemical nature. The process of chlorination creates disinfection by-products, which become dangerous to health when people encounter them in excessive amounts.¹⁴ The principles of green chemistry promote the creation of safer chemical substances, the decrease of chemical materials and the development of environmentally safe waste management methods.¹⁵

The modern water treatment process uses advanced electrochemical technologies, which provide both stronger contaminant removal capabilities and better environmental protection than traditional methods. The three methods of electrocoagulation, electrooxidation and electro-Fenton processes function as sustainable solutions that match decentralised treatment systems used to treat various contaminants in rural and remote areas because they operate efficiently without requiring substantial chemical additives.^{16,17} Piezocatalysis, which is a newly developed advanced oxidation technique, serves as an effective solution for destroying multiple types of environmental pollutants while simultaneously eliminating dangerous microorganisms. The combination of these advanced techniques shows how energy-driven and chemical-minimised methods can create new possibilities for designing efficient and sustainable wastewater treatment systems.¹⁸

Nature-inspired treatment strategies have begun to receive greater recognition since they have been established as effective treatment methods. The three systems, constructed wetlands, algae-based systems and bio-electrochemical reactors, all depend on their natural biological and chemical abilities to treat wastewater through nutrient and contaminant removal.¹⁹ The advanced chemical treatment technologies better treat waste through their combination with nature-based systems, with both high efficiency and environmental sustainability.²⁰

Circular water systems and resource recovery

The future of water sustainability lies in transitioning from linear water use toward circular water management. Wastewater should not be treated as a disposal issue because it contains valuable resources, which include nutrients, energy and reusable water.²¹

Chemical technologies enable the recovery of phosphorus and nitrogen from wastewater, which can then be reused as fertilizers in agriculture. Advanced oxidation and membrane systems provide facilities with a treatment solution that allows to safely reuse of wastewater for industrial operations and agricultural irrigation.²²

Several water-scarce regions practice water reuse, which includes Singapore and parts of the Middle East. The systems depend on advanced chemical treatment processes that include membrane filtration, ultraviolet oxidation and activated carbon adsorption as their primary treatment methods.²³

Chemical innovation for decentralized water access

Centralised treatment plants cannot be constructed in remote areas or low-income areas. Decentralised water purification technologies, which use chemical principles of designable systems, offer the main advantage of creating affordable systems that can be expanded to meet increasing water treatment needs.²⁴

The system includes three components: portable filtration units, solar-driven desalination systems and low-cost adsorbent filters that use locally available agricultural waste materials.²⁵ Biochar, which comes from agricultural waste materials, operates as a method to eliminate heavy metals and organic contaminants while establishing an environmentally friendly solution for waste disposal.²⁶

Point-of-use treatment systems that use silver nanoparticles, activated carbon and ceramic membranes are already enhancing drinking water quality in rural areas. The combination of such technologies with community education and policy support functions as an effective way to decrease waterborne diseases.²⁷

Integrating science, policy, and society

Sustainable water management requires a strong integration of scientific research, policy frameworks, and societal participation. Governments use evidence-based policymaking, which relies on scientific data to create water resource protection strategies and sanitary access improvement plans. This strategy supports Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy) and accomplishes SDG 6 (Clean Water and Sanitation) by leveraging to the Water-Energy-Food nexus. SDG 17 (Partnerships for the Goals) will be accomplished with the support of international collaborations involving scholars, citizens, and government representatives. Countries can establish integrated sustainable water management systems that support the 2030 Agenda for Sustainable Development through science-policy-society connections.²⁸

Conclusions

The global population requires sustainable clean water supplies, which represent one of the most urgent challenges that the twenty-first century must resolve. Chemical sciences enable the development of energy-efficient and eco-friendly treatment technologies, which include systems for precise pollutant detection. The trend toward environmentally friendly solutions is exemplified by methods such as nature-based systems, advanced membranes, biopolymer-based treatments, and processes powered by renewable energy. Sustainability requires different approaches, which specialists must develop according to specific environmental conditions and resource availability in each region. Intelligent decentralised systems will transform water management through their use of artificial intelligence, real-time monitoring and cyclic water reuse capabilities. The ultimate goal is to establish strong systems that prevent contamination from entering water supplies, thereby securing clean drinking water for all future generations.

Statement on use of AI

No AI was used in the preparation of this essay. The graphical abstract was designed using Canva.

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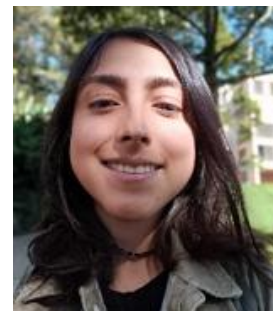
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Finalist

Mechanochemistry for sustainable water access: destroying contaminants, harvesting water, and purifying what remains

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Context

Water is not just a resource, it is the substance of life. But even in 2026, the language we use to describe its disappearance has become dangerously inadequate. The term “water crisis” applied in the same way to a single dry season and to the multi-decadal collapse of aquifers has become so normalized that it mobilizes no policy nor conscience. Madani proposes a more precise and honest term: water bankruptcy -a crisis state in which human withdrawals exceed the hydrological carrying capacity of a system,¹ causing irreversible damage to its natural resources. Unlike financial bankruptcy, water bankruptcy is irreversible: dried wetlands, compacted aquifers, subsided land, and extinct species cannot be restored within any human timescale. Adopting this diagnostic label is essential for transformative bankruptcy management, which replaces restorative crisis management with a fresh start focused on adapting to a “new normal” rather than attempting to resurrect a past that no longer exists.

The scale is planetary and climate change amplifies this situation by shrinking renewable inflows while simultaneously increasing agricultural and urban demand. The most common policy response is to build new dams, dig deeper wells and expand desalination facilities. However, this approach does not address the fundamental issues of how we developed our economies in the first place.

Into this context, the United Nations Sustainable Development Goals (SDGs) provide both a moral and a practical framework. SDG 6 (Clean Water and Sanitation) aims to achieve universal access to safe drinking water by 2030; SDG 3 (Good Health and Well-Being) recognizes that contaminated water remains a leading cause of preventable diseases worldwide; SDG 13 (Climate Action) is inseparable from water, because water systems and the climate system are coupled. The American Chemical Society has identified these, and SDG 9 (Industry, Innovation and Infrastructure), as priority goals for the chemical sciences.² Therefore, chemistry is not merely an observer of water bankruptcy, it is one of the few disciplines capable of acting at the intersection of all these goals simultaneously.

Analysis: three mechanochemical pathways

Mechanochemistry, the use of mechanical energy to drive chemical reactions through high-energy ball milling, without solvents and at modest temperatures, has emerged as a green, scalable technique that is well-suited to addressing the issue of water scarcity. The principle consists on mechanical forces from impact and shear that generate localized energy and defects to enable transformations inaccessible by thermal routes, yielding highly reactive materials at a fraction of the energy and solvent cost of conventional wet chemistry. Three applications define mechanochemistry's contribution to sustainable water access.

Destroying forever chemicals.

Per- and polyfluoroalkyl substances (PFAS), known as “forever chemicals” characterize the most demanding dimension of modern water contamination. Their carbon–fluorine bonds -among the strongest in organic chemistry- resist biological degradation, accumulate across food chains, and have been linked to liver and kidney damage, immune suppression, and elevated cancer risk.³ The U.S. Environmental Protection Agency (EPA) now enforces a limit of 4 parts per trillion for perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in drinking water, a concentration that cannot be reliably achieved by conventional treatment methods.³

Ball milling of PFAS with co-milling agents generates the radical species and defect-rich surfaces necessary to cleave C–F bonds. As summarized in Table 1, the diversity of effective agents is remarkable. As an example, Boron nitride (BN) is a piezoelectric material, meaning its crystal structure allows it to develop strong electric dipoles when subjected to mechanical stress. In this order, it can drive redox reactions and could achieve 100% defluorination of PFOS and PFOA within 2 hours. It does not require additional caustic chemicals, external heat,

or high pressure to be effective.³ Silica (SiO_2) achieves near-complete degradation (99.95–100%) of five perfluoroalkyl sulfonates, forming stable Si–F bonds that immobilize fluoride rather than releasing it to the environment. Also, while zero-valent iron (ZVI) alone achieves 84.4% degradation and ferrate (VI) alone achieves 50.1%, their combination achieves near complete degradation (100%) and high defluorination (93.1–95%) within 4 hours, through the formation of synergistic reactive iron species which accelerate electron transfer -critical for breaking carbon-fluorine (C-F) bonds.³ In general, PFAS mechanodegradation proceeds through five stages: activation, head group cleavage, intermediate formation, iterative chain shortening, and final mineralization. Industrial-scale validation using 267-liter horizontal ball mills in real contaminated soils proves this technology is a scalable solution for protecting drinking water sources.³

Harvesting water from air

While PFAS remediation addresses the contaminants in water, atmospheric water harvesting addresses the generation of water where none exists, which is critical in arid zones that are most vulnerable to water bankruptcy. MOF-303, the aluminium-based metal-organic framework $\text{Al}(\text{OH})(\text{HPDC})$ -where HPDC is the organic linker 1H-pyrazole-3,5-dicarboxylate-, is among the most efficient materials for this application. Under desert conditions (10% relative humidity, 27°C) it can produce 0.7 litres of water per kilogram of material per day.⁴

The science behind MOF-303 lies in its pore chemistry. Molecular dynamics simulations reveal that pyrazole nitrogen atoms act as catalytic nucleation sites, enabling condensation of water vapor into small, loosely hydrogen-bonded clusters. Water inside MOF-303 forms an average of only 1.02 hydrogen bonds per molecule compared to 2.44 in liquid water, existing in a condensed vapor-like state that is captured from humid air yet released with minimal thermal input.⁴ The framework acts as a scaffold that initiates cluster formation while its hydrophobic surface elements control cluster size, preventing full condensation that would be difficult to extract.

Conventionally synthesizing MOF-303 requires solvothermal conditions at 100°C for 15 hours. The mechanochemical route reduces this to 1 hour of water-assisted ball milling at 500 rpm.⁵ In addition, the resulting material exhibits a specific surface area of 1180 m^2/g , exceeding the solvothermally produced equivalent (994 m^2/g), among the highest reported. Higher crystallinity in the ball-milled product is attributed to the more uniform dispersion of reactants under mechanical action. For communities in water-scarce regions of the Middle East, sub-Saharan Africa and South Asia, a mechanochemically produced MOF-303 sorbent could provide resilient, decentralized access to water without reliance on failing aquifers or costly desalination infrastructure.

Purifying what remains

In addition to PFAS and water harvesting, water bodies worldwide carry heavy metals (such as chromium, arsenic and lead), as well as antibiotics, dyes and pesticides. The removal by conventional treatment methods is either incomplete or too expensive. Mechanochemistry provides a versatile platform for producing the reactive nanomaterials and heterogeneous catalysts needed to address this broader range of contaminants.⁶

Ball milling of ZVI with elemental sulfur creates a high-performance material known as mechanochemically sulfidated ZVI whose surfaces are dominated by FeS and iron oxides that protect the core iron from further passivation. The Fe^0/FeS interface is much more conductive than iron oxide. This allows electrons to flow more easily from the metallic iron core to the surface, where they can react with contaminants. Also, the sulfur-based coating increases the material's hydrophobicity, which improves its binding affinity toward organic pollutants like chlorinated compounds and for the removal of inorganic contaminants like hexavalent chromium.⁶

Photocatalysis can remove dyes, antibiotics and pesticides, by using light energy to activate a semiconductor material to break down these organic pollutants into harmless substances like water and carbon dioxide. The process initiates when the catalyst absorbs photons, causing electrons to move, leaving behind positively charged holes. To effectively degrade contaminants, these photo-induced charge carriers must migrate to the catalyst's surface to react with water and oxygen, generating powerful reactive oxygen species (ROS). Nevertheless, photo-generated electrons and holes tend to recombine rapidly. High-energy ball milling exfoliates compounds like graphitic carbon nitride $\text{g-C}_3\text{N}_4$ into high-surface-area nanosheets and subsequently forms heterojunctions with other semiconductors, which improves charge carrier separation to accelerate organic pollutant degradation.⁶

Conclusions

The three mechanochemical pathways described here do not operate independently, they form a coherent and complementary architecture. PFAS remediation protects existing water sources from one of the most insidious contaminant classes known. MOF-based atmospheric water harvesting enables the generation of new water in

arid regions where bankruptcy is most advanced. Purification via nanomaterials provides the catalytic tools needed to remove heavy metals and organic pollutants from water. Together, they represent a systemic chemical response to structural failure.

Unlike a temporary "crisis" water bankruptcy represents a persistent state of insolvency and irreversible damage to natural capital because it implies critical situations such as compacted aquifers, subsided land, melted glaciers, and extinct species. This problem demands not crisis management, which focuses on restoration, but bankruptcy management, which demands transformation.

The same human ingenuity that created PFAS, that enabled industrial-scale agriculture to drain aquifers within a single generation, and that built cities in deserts, is now being called to undo those consequences. Mechanochemistry could be seen as a tool to do more with less, to build without burning, to heal without poisoning. This approach aligns with the SDGs and is the kind of moral commitment that water bankruptcy demands of us. We did not inherit a water-bankrupt world. We made it. The defining question for the next generation of chemists and policymakers is whether we have the imagination -and the will- to create a different future.

Table 1. Mechanochemical co-milling agents for PFAS degradation: key byproducts and performance

Co-milling agent	PFAS targeted	Byproduct	Environmental concern	Max degradation
KOH	PFOS, PFOA, 6:2FTSA	KF (toxic, soluble)	Groundwater contamination risk	Up to 99% (3–6 h)
SiO ₂	PFASs (PFBS–PFOS)	Si–F (stable)	Low; non-leachable	99.95–100% (3–12 h)
Al ₂ O ₃ + PS	PFOA, PFHxA	SO ₄ ^{2–}	Non-toxic; ionic balance	Up to 99% (2 h)
La ₂ O ₃	PFOS, PFOA, PFHxS, PFBS	LaOF, La(CO ₃)F	NA; recyclable	100% (4–8 h)
BN (piezo)	PFOS, PFOA, PFAS in sediment	B–F, N–F (stable)	Low leachability	100% (2 h)
ZVI + ferrate(VI)	PFHxS	Fe(III)/Fe(OH) ₃	Non-toxic; sludge residue	Up to 100% (4 h)

Adapted from Ammar et al.³ PS = sodium persulfate; ZVI = zero-valent iron; BN = boron nitride. "NA" = not yet assessed.

Statement on use of AI

During the preparation of this manuscript, the author used Claude.AI 4.6 in order to improve the language and readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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