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Protection over restoration to ensure water sustainability

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Plastics pollution, persistent chemical contamination and inadequately treated wastewater are three key aspects that hinder access to safe and affordable water for all. We argue that a strong priority on pollution avoidance, research for remediation, and tighter regulation and monitoring must be implemented to make progress.

The ambitious goal of achieving universal and equitable access to safe and affordable drinking water by 2030 was outlined by the United Nations (UN) in 2015[1]. This goal is now unlikely to be met[2]. In particular, in contrast to pathogen contamination, chemical water pollution remains a significant but under-scrutinized issue[3]. Water bodies bear the brunt of the 2 billion tons of synthetic chemicals produced annually globally[4] and of the 540,000+ chemical substances registered with limited environmental fate data[5]. As such, a substantial fraction of water bodies are severely polluted[6] and water is the environmental medium with the highest number of detectable chemical contaminants[7] (Fig. 1).

Access to safe water is remarkably inequitable. Two thirds of the world's population experience severe water scarcity every year[8]. For these people, water low on environmental contaminants is an unattainable luxury. Water contamination and water scarcity are emphasized in the UN Sustainable Development Goals, but these two aspects are rarely linked – although clearly, contaminated water cannot be used to fulfill most of human's water-related needs. Global water inequality is causing substantial water-related forced displacement, not only in the Middle East and North Africa, but increasingly also in the rest of the world[8,9].

These threats to our water systems are neither novel nor unrecognized. Nevertheless, at the 2023 UN Water Conference, which was aimed at assessing the progress made mid-way through the International Decade for Action ("Water for Sustainable Development", 2018-2028), practical solutions were scarce and centered on the vague recommendation of fostering "innovative, affordable local solutions"[10].

To highlight science/policy gaps in water sustainability, we considered and compared three distinct and pressing water issues: pollution by micro- and nano-plastics; contamination by per- and poly-fluoroalkyl substances (PFAS), sometimes termed 'forever chemicals'; and the use of wastewater in agriculture. Based on discussions at a conference on water management, contamination and toxicity[11], we identify five priorities to make progress with the United Nations' water-related goals: (1) heavily favor pollution prevention strategies, i.e. stopping contamination at the source; to be paired with (2) research into degradation and removal of contaminants already present in the environment; (3) mapping of water contaminants and research into their health effects; (4) transparent communication of presence and health effects of contaminants to stakeholders and the public; and lastly (5) tightening regulations and closing loopholes.

Recycling plastics is part of the problem

It is now clear that micro- and nanoplastics are an integral part of our lives as they are detectable in a wide array of human tissues including blood, lung, placenta, and testis[12–15]. Exposure to micro- and nanoplastics is associated with negative health outcomes in laboratory models and humans including neurotoxicity, inflammation, cancer and cardiovascular events[11,16,17]. However, there is still a large gap in our understanding of their generation at all stages of their life cycle and of their environmental fate[18,19]. Nevertheless, there is a heavy focus of international agreements on the circularity of the plastics economy that ignores the predicted dramatic 44-fold increase in micro- and nanoplastics generation as a result of increased mechanical recycling or downcycling of plastics[20].

Equally concerning is the widespread and persisting confusion regarding the recyclability, biodegradability, and compostability of plastics and bioplastics, and their environmental impacts. For example, products labelled as bioplastics may still contain fossil-fuel generated plastic material (e.g. plastics made of fossil-based but biodegradable polymers) while the vast majority of compostable plastics are only compostable following processes solely found in industrial composting facilities that are still not widely available[21–23]. This confusion combined with a lack of adequate methodologies to assess plastic biodegradability in water and marine environments[24,25] all cast strong doubts on the promises of plastic biodegradability in water[26]. Indeed, the environmental degradation and composting of "biodegradable" plastics as well as the mechanical recycling of plastics lead to the generation of large amounts of micro- and nanoplastics[20–24,26]. We therefore propose that secondary micro- and nanoplastics, that is those that originate from plastic degradation, need to be taken into account when assessing the effective footprint of plastic products and when trying to address plastic contamination. Elimination and reduction of plastic use is the only truly sustainable intervention (Fig. 2) and should be heavily prioritized over recycling, composting, or other environmental biodegradation strategies.

Since only 9% of plastics ever produced have been recycled, or, more accurately, downcycled, i.e. turned into products of lesser quality[27,28], most plastics manufactured are still present in our environment. Thus, a second, parallel focus should be on the development and implementation at scale of bioengineering strategies for the degradation of existing plastics but inclusive of micro- and nanoplastics in water effluents[29]. Again, an emphasis on micro- and nanoplastics in environmental plastic degradation strategies will be necessary to avoid their generation during in situ plastic degradation the processes[30].

Significant roadblocks in the implementation of this vision will likely originate from the need for harmonization on the definition and assessment of microplastics[31], a strong and continuing involvement of oil

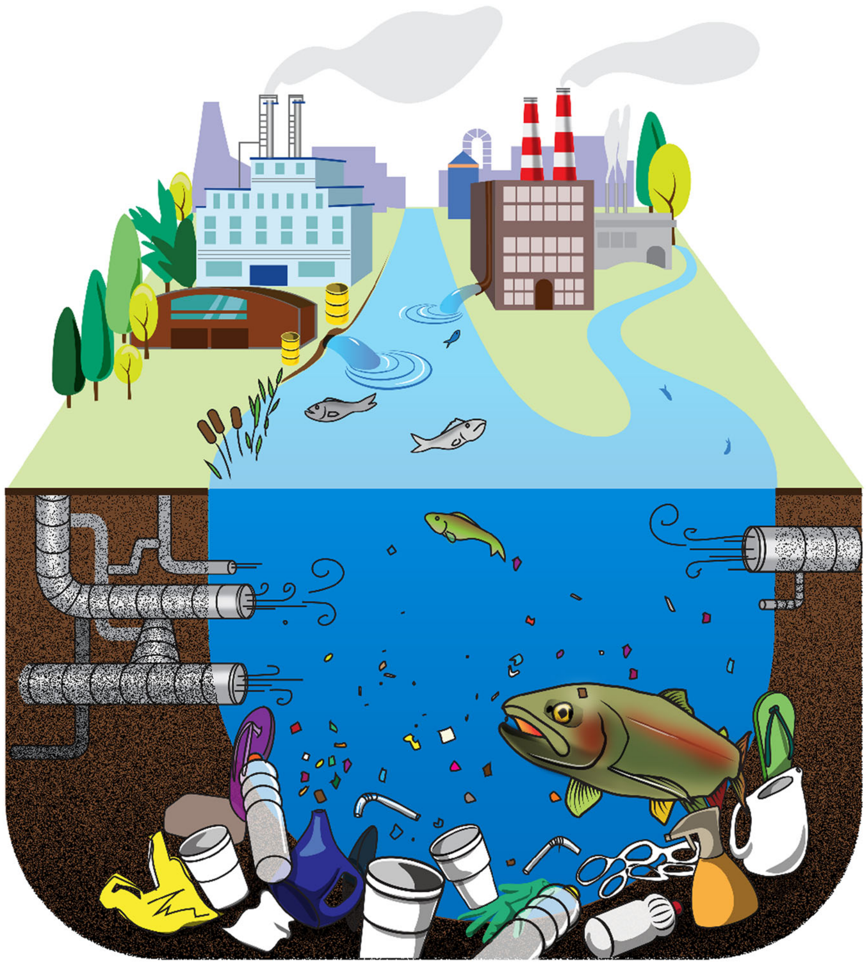

Fig. 1 | Water unsustainability.

and plastic-industry lobbyists in drafting international agreements[32–34], the purposeful design of exemptions to elimination efforts[35], and the lack of transparency of the petrochemical industry[36].

Comprehensive regulations for PFAS

Per- and poly-fluoroalkyl substances (PFAS) represent a large family of over 15,000 synthetic chemicals[37] that are omnipresent in the environment[38] and that have sometimes been termed 'forever chemicals' because of their remarkable environmental persistence[39]. PFAS are used in many materials for their high performance physico-chemical properties, and are found, for example, in water-resistant clothing, air conditioning, food packaging, cookware, medical devices, and many more[40]. In 2020, in the EU alone, 75,000 tons of PFAS were emitted, and without regulation, it is estimated that 4.4 million more tons may be emitted in the next 30 years[41]. Because of their production volume and persistence, PFAS are an important water contaminant widely found in US and European drinking water systems, as well as in rain water[42] and in over 75% of US water streams[43–46].

Exposure to legacy PFAS, i.e. PFAS phased out of production in the early 2000's due to safety concerns, causes a plethora of health effects including the deregulation of lipid metabolism, lower birth weight, and cancer[47]. Unfortunately, the new generation of PFAS chemicals claimed to be safer than the legacy PFAS are also showing clear toxicological effects[47].

Current legislation in Europe and in the US allows widespread PFAS contamination in water to persist. For example, since 2000, EU's water quality and quantity are regulated through the Water Framework Directive and its daughter directives, such as the Groundwater Directive and the Environmental Quality Standards Directive[48], with the aim to ensure that all the fresh- and groundwater bodies achieve good ecological, chemical, and quantitative status by 2027. In parallel, REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)[49] regulation "aims to protect human health and the environment against the harmful effects of chemical substances", among which are PFAS. Despite these ambitious legislations, numerous water bodies - both surface and groundwater - still fail to achieve 'good status' due to widespread chemical pollution[50,51]. Because there is still a great need to measure the extent of PFAS environmental contamination, the unique Forever Pollution collaborative project between journalists and scientists has comprehensively mapped PFAS contamination in water, soil or living organisms[52]. Their work has identified ~23,000 PFAS contaminated sites, many in water bodies, and over 2300 hotspots across Europe[52].

To address the widespread and persistent environmental contamination by PFAS, US[53,54] and European[55] legislations to restrict these chemicals have been proposed. Some of these legislation drafts appear significantly more advanced than those addressing micro- and nanoplastics, since they are based on a broad definition of PFAS, which would regulate, in theory, the

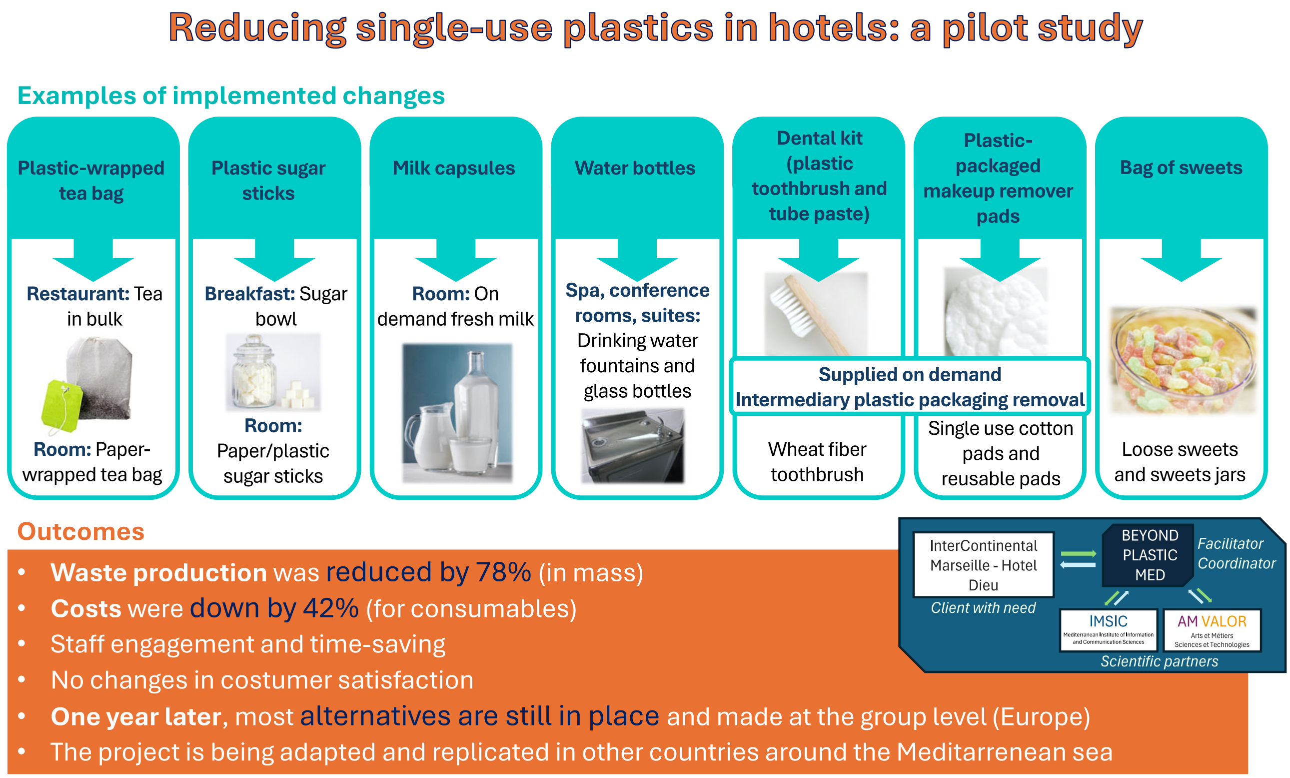

Fig. 2 | A pilot hotel case study towards reduction of single-use plastics in hotels. Plastic elimination can be implemented without delay, as successfully demonstrated by the efforts of the non-governmental organization BeyondPlasticMed. To curtail the more than 3000 billion particles of microplastic found in the Mediterranean Sea, the most polluted sea in the world, BeyondPlasticMed developed a toolkit method for removing single-use plastics from hotels that was successfully implemented at the InterContinental Marseille – Hotel Dieu, France. The methodology was comprised of six steps: (1) Assess the current state of plastic use at the hotel location (2) Prioritize the single-use plastics (SUPs) that will be tackled (3) Develop strategies to remove, reduce, or replace these SUPs (4) Select the best sustainable alternative to SUPs (5) Trial run new alternatives in hotel environement (6) Gauge trial run impact. As a result of this initiative, waste production was reduced by 78% and costs for consumers went down by 42% with no change in consumer satisfaction. The hotel staff was engaged, and one year later most measures were still in place. The project is now being expanded to locations around the Mediterranean sea including in Tunisia, Greece, and Spain.

entire family of PFAS molecules. However, many of the shortcomings of current legislation, such as patchy monitoring data, an insufficient application of the polluter-pays principle, and pre-designed loopholes based on use are likely to apply to the proposed draft legislations as well.

The need for improved implementation and enforcement of environmental laws was highlighted in the 2021 EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'[56]. The aforementioned purposely designed loopholes are of particular concern. For example, despite the estimated cost of €238 billion/year to remove PFAS from European drinking and wastewater, emission permits are allowed, and compensation deals can be struck in ways not proportionate to the emission's environmental impact[57]. In California, while outlining a restriction of PFAS from many consumer products, the current Governor vetoed their proposed restriction from cleaning products[58]. Meanwhile, in Europe proposed derogations, some up to 12 years, are proposed for PFAS used as fluoropolymers and in clothing[59]. With more than 70 years of large-scale PFAS production and with over 15,000 PFAS in use, the establishment of drinking water limits of only 6 PFAS by the US Environmental Protection Agency falls short of its description as a major victory[60].

PFAS regulation must be accelerated and broadened to all uses, with low or no thresholds and with a strong enforcement of polluter-pay principles[61] that will directly be used towards improved monitoring and remediation efforts.

When water is most needed: the challenges of wastewater use for agriculture

With over 80% of its population enduring extremely high water stress, the Middle East and North Africa region is the most water stressed region in the world[62]. This precarious state is only expected to worsen as it is intensified by climate change, limited water resources, inflation in the population size from local and immigration flow, as well as by the conversion of natural environments by human action[63]. Water scarcity causes significant economic losses and environmental degradation, which affects agricultural production: over 50% of water withdrawal is used for agriculture[63,64].

In this context, reuse of treated wastewater is viewed as a priority solution for agricultural sustainability[65]. However, by 2020, less than 11% of municipal wastewater was directly reused in the Middle East and North Africa region[66,67]. Barriers to more widespread implementation of treated wastewater reuse include low trust level; lack of funding, infrastructure and expertise; fragmented governance; and unclear, ineffectively implemented regulations without enforcement[65,68].

Box 1 | A case study in the Algerian Sahara

In the Berriane region in the north of Ghardaïa (center of Algerian Sahara), an agricultural perimeter called Oued El Bir (300 ha in total) was officially created in 2013, downstream of a wastewater treatment plant. However, inadequate project management and poor coordination between the institutional actors involved in the resource reuse process have severely limited the direct use of treated wastewater for agriculture. As part of the Massire project financed by IFAD (2018–2024), the objective of the study was to analyze the infiltration of insufficiently treated sewage from the treatment plant into the groundwater which is then recaptured and therefore indirectly reused by farmers accessing it through their own boreholes. The main results indicated that while there is contamination of 4 out of 9 analyzed boreholes with pathogens (total coliforms, fecal coliforms, streptococcus and *E. coli*), there is no evidence of widespread mixing of wastewater and groundwater. Current efforts are focusing on the monitoring of microcontaminants to better understand the impact of indirect water reuse on water quality and better delineate the possible agricultural practices and crops for which the unregulated use of this water might be safe.

One common thread connecting these limitations is the issue of chemical contamination in treated wastewater. Despite regulations across the Middle East and North Africa, farmers must use what is available, which can be untreated or inadequately treated wastewater from a mix of municipal and industrial sources[66] and therefore contaminated with a wide variety of chemicals such as pharmaceuticals, pesticides, metals, endocrine disrupting chemicals, etc.[69,70]. Thus, intentional use of untreated wastewater occurs in many peri-urban areas while unintentional use by farmers happens via the contamination of groundwater downstream of released untreated or insufficiently treated wastewater[69]. Importantly, the removal of micro-contaminants and contaminants of emerging concerns such as endocrine disruptors and PFAS cannot be achieved through the treatment levels currently deployed[69,71]. The recent case study of water reuse in the Algerian Sahara (Box 1)[72] highlights the need to (1) develop capacity in not only building but also operating and maintaining wastewater treatment plants to sustain agriculture, (2) deploy comprehensive environmental monitoring efforts inclusive of chemical pollutants, and (3) clear communication and coordination of the treated water uses (direct or indirect, Box 1) with the farming communities[70]. Challenges to the implementation of participatory water governance are a lack of trust in the government, changes in government and their policies, shallow consultation process, and counter-productive involvement of the private sector[73,74].

Towards effective global pollution strategies

Our focus on these three salient water-related contamination problems – plastics, persistent chemicals, and wastewater use – reveals important common bottlenecks to achieving clean water goals. We suggest the following paths forward.

1. Protection over restoration. Contaminant removal strategies are often insufficient or inadequate, such as with micro- and nanoplastics in drinking water[19]. Chemical replacement often leads to regrettable substitution as seen with PFAS[47] but also many other contaminants[75]. Policies aiming to control the use of contaminated water are often ignored, especially in water-stressed areas[72]. We argue that strategies for the elimination, or at least the significant reduction of contamination, should be heavily prioritized in all water sustainability endeavors over other approaches, such as recycling, environmental capture, policy changes, etc.
2. Comprehensive data collection. The recent finding that bottled water contains several hundreds of thousands of micro- and nanoplastics[76] highlighted how little we know about their presence in our environment as well as the need for more accurate and sensitive detection methods[76]. Across the three water issues discussed here emerges a clear need to better map water contaminants across water bodies and sources[52,72,77,78], and to gain a deeper understanding of the health effects of exposure to water contaminants, including substitutes to chemicals that are being phased out[79,80].
3. Improved communication. Communication to consumers and policy makers is sorely needed around the life cycle of water pollutants, to address misunderstandings about their environmental fate. The lack of transparency surrounding the presence of water contaminants combines with the equal lack of clarity about the impact of human practices on water contamination. The confusion surrounding plastic biodegradability, recyclability, and compostability – which often leads to a worsening of plastic pollution[21–23] – is one example, but there is also a lack of awareness and trust in the safety of treated reused water[72,81–83]. Dissemination of knowledge on these issues will empower stakeholders to enact changes at all levels from practice to policy-level. Such efforts are especially important at the level of the general public to allow people to make smarter and more sustainable decisions and to maximize consumer pressure.
4. Research towards environmental removal and degradation. Humans have transformed their environment and created a world in which, for the foreseeable future, they will live alongside the chemicals and particles they produced. While elimination/reduction efforts need to be prioritized to prevent increased contamination, scientifically-sound removal and biodegradation methods must be developed and scaled to address the current, long-lasting, water contamination problem[84–86]
5. Broadening and tightening of regulatory loopholes. Draft versions of policies to regulate primary micro- and nanoplastics and PFAS in the US and in Europe already contain exceptions that are perhaps better termed loopholes[57,59]. Regulations need to be broadened to also include secondary micro- and nanoplastics (i.e. not intentionally produced as such but instead generated from degradation or recycling) as well as a closing of existing loopholes. Policies should include strong polluter-pay counter-incentives commensurate to the scale of the damage to our ecosystems and health. Finally, it is important that these policies find support across the political spectrum and communities to ensure their persistence, in particular in the context of wildly fluctuating political landscapes in the world[87,88].

Achieving water sustainability in the decades to come will require a shift in focus and bolder steps and actions than those currently considered by international and national governmental bodies.

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Competing interests
The authors declare no competing interests.

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