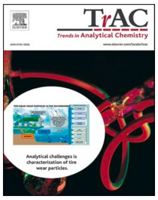
Trends in Analytical Chemistry 181 (2024) 118000

Contents lists available at ScienceDirect

Trends in Analytical Chemistry

journal homepage: www.elsevier.com/locate/trac



Plastic problem solved? Environmental implications of synthetic hydrophilic polymers across ecosystem boundaries

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ARTICLE INFO

Keywords:
Water-soluble polymers
Liquid polymers
Polymers in liquid formulations
Polymer flocculants
Superabsorbent polymers
Hydrogels
Nanoplastics
Plastic debris
Ecosystem functions

ABSTRACT

Synthetic hydrophilic polymers are an emerging yet overlooked class of anthropogenic substances. Unlike particulate plastics, synthetic hydrophilic polymers can interact with water, which complicates studying their fate and effects in the environment. This review discusses the sources, fate, and effects of these polymers across ecosystem boundaries. We identified households, agriculture, and mining as major sources. Despite wastewater treatment, synthetic hydrophilic polymers enter natural waterbodies. Agrochemical and sewage sludge applications release them to soil. Sorption and coagulation processes, influenced by polarity and molecular weight, likely define their fate through aquatic and terrestrial systems. Slow biodegradation may favor their accumulation. To advance our understanding of their fate, analytical techniques need improvement. Ecotoxicity studies found acute effects but long-term and field studies on mixtures and interactions with other pollutants are lacking. All in all, the prevailing literature emphasizes benefits of synthetic hydrophilic polymers while neglecting potential negative consequences; this calls for precaution.

1. Introduction

The deliberate use of plastic products in modern society causes extensive pollution, probably exceeding the safe operating space of the planetary boundary of novel entities by now [1–3]. Plastic pollution research has so far focused on solid, usually hydrophobic and water-insoluble polymers, such as polyethylene or polystyrene, ranging from macroscopic debris (>1 cm) to microplastic (<5 mm) and nanoplastic particles (<1 μm) [4–6]. Yet, there is another emerging class of anthropogenic materials that has received little scientific attention despite an annual global production of 36.3 megatons (Mt) and uncertain environmental implications; that is synthetic hydrophilic or water-soluble polymers [7,8].

Synthetic hydrophilic polymers, like polyethylene glycol (PEG), polyvinyl alcohol (PVOH), polyacrylamides (PAMs), or polyacrylates (PAAs), are widely used in household cleaning and personal care products, paints, industry, wastewater treatment, and agriculture [7]. They contain polar or charged functional groups, such as hydroxyl, carboxyl, carbonyl, or amide moieties, which enable molecular interactions with water and other polar compounds [9]. Contrary to hydrophobic polymers, hydrophilic polymers are swellable, dispersible, or completely soluble in water [10,11]. The variability and dynamics of those properties make the fate of synthetic hydrophilic polymers in the environment particularly challenging to study [12,13].

Once released into the environment, synthetic hydrophilic polymers are subject to weathering, potentially enhancing their mobility and distribution between environmental compartments [4]. However, neither the environmental fate of virgin synthetic hydrophilic polymers nor that of their metabolites have been systematically investigated. Furthermore, the potential effects of synthetic hydrophilic polymers are virtually unknown and have mostly been assessed in simplified acute toxicity tests. Only recently, Wang et al. [8] reviewed water-soluble

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https://doi.org/10.1016/j.trac.2024.118000
Received 22 December 2023; Received in revised form 20 September 2024; Accepted 5 October 2024

polymers but focused on aquatic environments while mostly neglecting terrestrial systems.

Going beyond the limited and fragmented knowledge of synthetic hydrophilic polymers currently available in the scientific literature, this review aims to scrutinize the environmental implications of this emerging substance class across ecosystem boundaries: from urban wastewater streams to soil, natural surface waters, sediment, and groundwater. We first analyze use and emission scenarios to identify the major sources of synthetic hydrophilic polymers. Based on this, processes governing the fate of synthetic hydrophilic polymers and potential impacts on ecosystems are evaluated. We further discuss upcoming methods for quantifying the fate and effects of synthetic hydrophilic polymers in different environmental matrices.

2. Methods

We searched Scopus, Web of Science Core Collection, and Google Scholar literature databases for the following search term: “synthetic” or “artificial” appearing near “water-soluble”, “liquid”, “hydrophilic”, or “superabsorbent” “polymer”. The search term was amended with application contexts, such as “domestic”, “urban”, “industry”, “environment”, “soil”, “agriculture”, “water”, or “ecosystem”, and relevant processes including keywords such as “fate”, “effect”, “impact”, “runoff”, “pathway”, “monitoring”, “treatment”, or “screening”. Keywords like “method”, “analysis”, “quantification”, or “chromatography” were added for analytical techniques. All in all, we found 966 references. Based on these findings and supplemented with cross-references, we selected 287 original research articles, 94 reviews, 17 books or book chapters, and 12 reports, preprints, and conference proceedings for further evaluation.

3. Same but different: properties and use of synthetic hydrophilic polymers

3.1. Definition and classification

While plastic particles are uniquely defined by their anthropogenic origin, solid state, and insolubility in water [6], there is no such uniform definition for other polymers. So far, non-solid polymers have been described as “hydrophilic” [10,14,15], “water-soluble” [8,16,17], or “liquid” [7,18] to distinguish them from particulate plastics. Although definitions based on macroscopic material properties like water solubility or aggregation state at ambient conditions have some merit, they fall short of unambiguously categorizing specific polymer types. For instance, PEG solubility in water decreases with increasing molecular weight of the polymer [19]. Most PAMs and PAAs form water-dispersible sols at low concentrations but gel or even cement at higher concentrations and in the presence of polyvalent cations [8,20]. Accordingly, a low-molecular-weight PEG would be defined as a “water-soluble polymer”, while excluding PEGs of higher molecular weight or PAA and PAM from that definition.

Since the molecular structure of the monomer remains the most-used identifier for distinguishing polymers, we suggest the term “hydrophilic” in line with polymer chemistry and materials science [9,10,14,15,21] to facilitate the classification of polymer types based on their monomeric structure. Since there are many natural hydrophilic polymers, like saccharides or peptides, man-made hydrophilic polymers further require the addition “synthetic” to define their origin. Semisynthetic polymers are derivatives of natural polymers artificially modified with additional functional groups or copolymers, such as methylcellulose and chitosan [15,22].

In the following, we refer to “synthetic hydrophilic polymers” to include all anthropogenic polymers capable of interacting with water through polar moieties, ranging from complete water-solubility to hydrogels dispersible or swellable in aqueous media [9–11]. The degree of interaction is controlled by the polymer’s polarity, molecular weight, its degree of physical and chemical crosslinking (Table 1), its concentration in a given medium, and the environmental conditions of the medium, like pH or ionic strength [23]. We use the attribute “water-soluble” to define a subgroup of hydrophilic polymers, along with further subgroups defining the polymers’ aggregation state or superabsorbent properties (Fig. 1).

3.2. Individual and domestic use

From the 36.3 Mt of synthetic hydrophilic polymers produced globally each year, the majority (31.1 Mt) is used for paints and adhesives. Another 1.2 Mt are produced to serve as additives to household cleaning and personal care products [7]. In those applications, synthetic hydrophilic polymers like PEG or polyvinylpyrrolidone (PVP) are added as thickeners, solubilizers, emulsifiers, or surfactants to alter the physical behavior of the product [24–26]. The superabsorbent PAA, which is used in diapers, amounts to a global annual production of 3 Mt [27].

A growing area of use are pharmaceutical and medical applications. Here, synthetic hydrophilic polymers are applied for their thickening purpose alike, but also as coatings, adhesives, surfactants, and binders for granulation [28–30]. They more and more replace natural, animal-derived substances like gelatin to improve pharmacokinetics and pharmacodynamics, facilitate drug approval, and acknowledge personal dietary preferences [31–34]. A novel application is the use of highly crosslinked hydrogels in tissue engineering, such as artificial cartilage and tendons [35–37]. Other than paints and adhesives, household cleaning and personal care products as well as pharmaceuticals inevitably enter sewage systems to undergo further wastewater treatment.

3.3. Flocculants in wastewater treatment

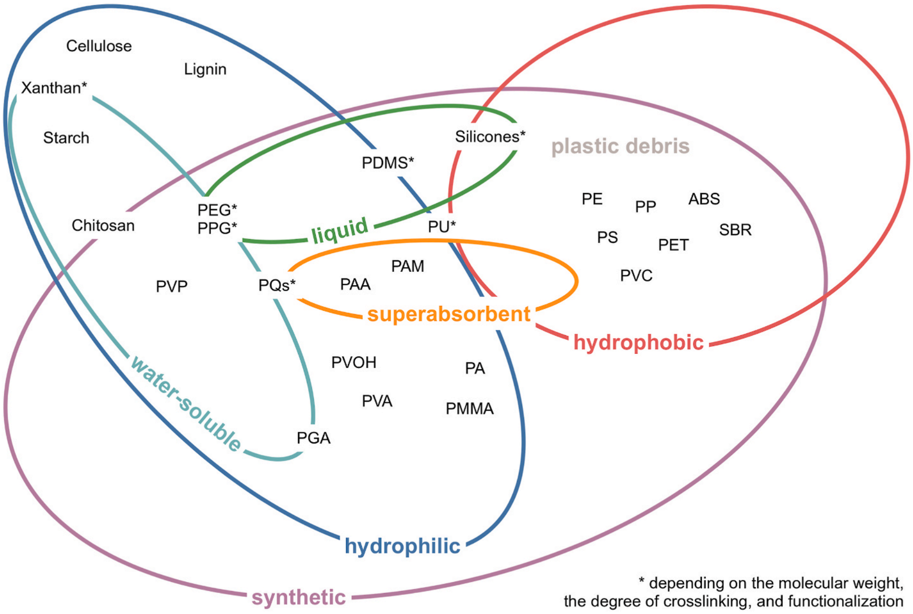
In wastewater treatment plants (WWTPs), synthetic hydrophilic polymers are applied as flocculants to facilitate coagulation and sedimentation of contaminants and to dewater sewage sludge. To this end, 1.5 Mt synthetic hydrophilic polymers are produced globally per year [7].

While metallic coagulants like $FeCl_3$ or $Al_2(SO_4)_3$ are state-of-the-art for removing suspended matter and phosphates, they are increasingly combined with synthetic hydrophilic polymers to enhance flocculation of organic contaminants [38–40]. Unlike metallic coagulants that mainly undergo electrostatic interactions [39,41], synthetic hydrophilic polymers are additionally capable of sorbing and entrapping contaminants within their hydrogel network [42]. PAA, poly(methyl methacrylate) (PMMA) copolymers, and PAM with molecular weights of 10 kDa–100 MDa are the most used flocculants in WWTPs for their low cost and easy functionalization with contaminant-specific moieties [18,38,39,41,43]. In addition, flocculants might be used for temporary maintenance and repair, during the decommissioning of cleaning stages, or in the event of malfunctions. Another advantage of polymeric flocculants is that the produced sludge is typically denser and has a lower water content compared to sludge produced with metallic coagulants only [39–41]. Due to the longevity of synthetic hydrophilic polymers, biodegradable polymers made of starch, lignin, or guar gum have sparked further research and development [39]. However, newly developed polymers often lack sufficient flocculation efficiency, which increases application amounts and material costs. A novel approach are graft copolymers consisting of a biodegradable backbone polymer and functionalized hydrophilic side chains [38,39]. Such copolymers enable higher flocculation efficiencies than starch- or guar gum-based polymers [42], while reducing the longevity of completely synthetic polymers [39,42].

Independent of the applied flocculant, polymer residues may remain both in treated wastewater and sewage sludge [26,43], from which they enter the environment via receiving waters or sewage sludge applications in agriculture.

Table 1
Properties and uses of major synthetic hydrophilic polymers.

Polymer	CAS no.	Mol. weight	Charge	Crosslinking	Major uses
Polyethylene glycol (PEG)	25322-68-3	0.3–6 kDa	neutral	no	household cleaning, personal care, agrochemicals
Polyvinyl alcohol (PVOH)	9002-89-5	20–400 kDa	neutral	no	agrochemicals
Polyacrylate (PAA)	9003-01-4	10 kDA – 100 MDa	anionic	yes	personal care, wastewater treatment, agrochemicals, soil remediation
Polyacrylamide (PAM)	9003-05-8	10 kDA – 100 MDa	anionic	yes	wastewater treatment, agrochemicals, soil remediation
Polydiallyldimethylammonium chloride (PQ6, pDADMAC)	26062-79-3	10–30 kDa	cationic	no	wastewater treatment
Polyvinylpyrrolidone (PVP)	9003-39-8	30–150 kDa	ampholytic	yes	household cleaning, personal care



* depending on the molecular weight, the degree of crosslinking, and functionalization

Fig. 1. Classification of synthetic hydrophilic polymers; ABS = acrylonitrile butadiene styrene, PA = polyamide, PAA = polyacrylate, PAM = polyacrylamide, PDMS = polydimethylsiloxane, PE = polyethylene, PP = polypropylene, PEG = polyethylene glycol, PET = polyethylene terephthalate, PGA = polyglycolic acid, PMMA = poly(methyl methacrylate), PPG = polypropylene glycol, PQ = polyquaternium, PS = polystyrene, PU = polyurethane, PVA = polyvinyl acetate, PVC = polyvinyl chloride, PVOH = polyvinyl alcohol, PVP = polyvinylpyrrolidone, SBR = styrene-butadiene rubber.

3.4. Agrochemicals

About 2.1 Mt synthetic hydrophilic polymers are produced annually for agricultural purposes [7]. This includes controlled release fertilizers and pesticides, seed coatings, and soil conditioners. To this end, a large variety of polymers are on the market such as PAA, PAM, PEG, polypropanediol, polyisoprene, PVOH, urea–formaldehyde resins, polyurethane (PU), polyesters, and polyurea [44–46]. Their application is projected to emit 50–400 kg ha^{-1} polymers per year into agroecosystems [47].

Pesticides and fertilizers are integral to modern agriculture but raise environmental and health concerns over the contamination of soil, plants, and groundwater, potentially involving human exposure or adverse effects towards non-target organisms [48,49]. Conventional agrochemical formulations blend the active ingredient with fillers, emulsifiers, or surfactants for safer handling and facilitated field application. Such formulations are typically limited in controlling the release of the active ingredient [50], which may lead to an unwantedly rapid dissipation of the active ingredient below minimum effect levels. For instance, nitrogen use efficiency for cereal production is only 33 % [51] due to the high solubility and mobility of nitrogen fertilizers. The remaining 67 % is lost to the environment by immobilization, denitrification, and volatilization of N_xO and NH_3 as well as NO_3^- leaching [52,53]. Eventually, this requires more frequent applications or higher application rates and implies higher material and labor costs. To reduce the environmental footprint of agrochemicals, controlled release technologies are a promising solution [54]: by stabilizing the active ingredient with synthetic hydrophilic polymers through encapsulation, crosslinking, or sorption [46], agrochemicals can be applied long-term and more targeted at a desired location and rate. These advantages led to an increase in the consumption of controlled release fertilizers from less than 0.2 % global market share in 1995/96 to 45 % in 2004/05 [55]. Ideally, this could help reduce agrochemical emissions into the environment [56,57]. For example, polymer-coated urea is used as controlled release fertilizer to protect nitrogen from heavy rain, dry periods, and biodegradation [58]. The quantity of required coating material varies, depending on geometric factors and the desired durability. On average, polymers represent about 15 % of the total weight of the product [59]. Besides biodegradable alginate or alkylcellulose beads [60], polymer coatings consist of PU, PAA, or even polyolefines [61].

Seed coatings and soil conditioners aim to improve the water and nutrient supply of arable crops [62]. Coating seeds with hydrophilic polymers enables quick water uptake and enhances germination after planting [63]. Similar to controlled release fertilizers, seed coatings can deliver pesticides locally and reduce their leaching [64,65]. They may further preserve seed quality during storage periods by acting as a physical barrier [66]. In forestry, planting holes are treated with synthetic hydrophilic polymers with superabsorbent properties like PAAs and PAMs to supply freshly transplanted trees with sufficient water [67,68]. Similarly, superabsorbent polymers are used as soil conditioners in horticulture to improve water retention and soil structure. Both applications are common in Europe and America. Yet, scientific studies are scarce and information is rather available in specialized magazines for operators [69,70]. What is known is that the use of superabsorbent polymers for conditioning agricultural soil seems limited in its geographic scope: in a global meta-analysis, Zheng et al. [71] found that 97 % of the 310 studies on the use of superabsorbent polymers in agriculture were from China and the remaining 3 % came from India, South Korea, and Iran. However, climate change may incite a wider application in the future.

3.5. Soil remediation

While synthetic hydrophilic polymers are commonly used for treating wastewater effluents, their application for remediating contaminated soil is less explored [72,73]. Few studies have demonstrated the potential of synthetic hydrophilic polymers in soil remediation so far, successfully stabilizing hazardous metals *in situ* and reducing their mobility and environmental impact [74]. In contrast to wastewater treatment, synthetic hydrophilic polymers are not recovered after remediation but remain permanently in the soil. Typical effective concentrations range from 1 to 6 g kg^{-1} PAA and PAM [74,75]. In geotechnical applications, semisynthetic hydrophilic biopolymers such as chitosan have been shown to promote the remediation of contaminated groundwater by coating sand particles and creating a plugging effect, which reduces the hydraulic conductivity and thereby contaminant mobility in soil [76,77]. However, those and other success reports often come from laboratory experiments [14,78,79], while there is a notable scarcity of literature dedicated to their utilization in the field.

Given the limited application of synthetic hydrophilic polymers in soil remediation, the overall mechanisms and processes involved can only be hypothesized: on the one hand, these polymers are expected to sequester contaminants through complexation and chelation [80,81]. Subsequent contaminant immobilization would reduce the potential for leaching and groundwater migration. On the other hand, synthetic hydrophilic polymers may help reduce soil erosion rates, by enhancing soil structural stability and thus minimizing downstream transport of contaminants [82–84].

By enhancing contaminant immobilization, soil structure stabilization, bioremediation, water and nutrient management, and erosion control, synthetic hydrophilic polymers have the potential to offer new solutions to current challenges in soil remediation. However, as synthetic hydrophilic polymers age and degrade, they may lose their intended remediation properties over time [20], potentially releasing previously stabilized contaminants back into the environment. Future research and development thus needs to evaluate whether the benefits outweigh the potential long-term consequences of deliberately introducing synthetic hydrophilic polymers into the soil.

3.6. Other uses

Beyond applications in WWTPs, agriculture, and soil remediation, synthetic hydrophilic polymers like PAM or PAA copolymers are used as industrial surfactants and lubricants for oil drilling and hydraulic fractionation, this is fracking [85–89]. The suitability for industry and mining stems from their high thermal and chemical stability, their versatile shear strength, and their ability to adjust the rheological properties of aqueous fluids [85,90]. PEG and PVOH are additionally used as anticorrosives [91]. Drilling fluids contain 20−700 g m^{-3} synthetic hydrophilic polymers [88]. Given the enormous water consumption of 15000–19000 m^3 per well [92], this amounts to 0.3–13 t of synthetic hydrophilic polymers released into the environment, which are probably incompletely recovered. Their environmental implications are, however, largely unknown [88].

Synthetic hydrophilic polymers are further applied in construction industry as suspending and curing agents in cement and mortar to counteract stress induced cracking [93,94]. Highly crosslinked hydrophilic polymers serve as a water reservoir to rehydrate unreacted cement particles and refill cracks [94]. The extent to which synthetic hydrophilic polymers may leach from self-curing cement is unknown but may be limited given their containment within the cement structure.

Other application areas are industrial cleaning, food industry, and paper production. In paper production, for instance, polymeric colloids are added to sorb to the grain surface and repel each other to prevent reaggregation [39]. Synthetic hydrophilic polymers from such applications are typically discharged into sewage systems for further treatment.

4. Fate of synthetic hydrophilic polymers: from source to sink

4.1. Potential pathways

From their point of use, synthetic hydrophilic polymers enter wastewater systems, natural surface waters, soil, and groundwater (Fig. 2). While some of these compartments may only be temporary, others will probably become a permanent sink of synthetic hydrophilic polymers. Yet, scientific research on the fate of synthetic hydrophilic polymers in the environment, their distribution between different environmental compartments, and potential transport mechanisms is still incomplete. As reviewed by Wang et al. [8], the fate of water-soluble polymers, a subgroup of synthetic hydrophilic polymers (Section 3.1), is governed by a combination of polymer properties and environmental conditions. In this regard, polymers would not differ much from classical chemical stressors like pesticides, pharmaceuticals, or engineered nanomaterials [95]. However, synthetic hydrophilic polymers may require further evaluation given their unique sorption and coagulation properties originating from their molecular size and functional groups (Section 3.3).

4.2. Urban wastewater

Synthetic hydrophilic polymers are released into the sewage system from households or via commercial and industrial wastewaters. Household cleaning and personal care products preferentially enter greywater, this is wastewater without fecal contamination. Polymer-containing pharmaceuticals are expected to end up in blackwater, which includes wastewater from toilets. In most countries, both are discharged by the same municipal sewer to the WWTP [96]. Although domestic products like diapers, household adhesives, or indoor paints are not meant to be disposed of via the sewage system, they may still enter wastewater streams due to improper disposal. By contrast, synthetic hydrophilic polymers in outdoor paints may be washed out during rain events and enter the sewer network via stormwater runoff, as documented for microplastics [97]. During heavy rainfalls, however, sewer overflows may redirect the combined wastewater directly into receiving waterbodies. In separated sewer systems, rainwater runoff is discharged directly into the watercourse without prior treatment [98].

The majority of synthetic hydrophilic polymers discharged to the WWTP are eliminated by precipitation, sedimentation, or flotation. PEG (0.3 kDa), for example, is removed by approximately 96 % during wastewater treatment [99]. To facilitate removal, however, more synthetic hydrophilic polymers are added as flocculants/coagulants and for sludge thickening in the main and side stream of wastewater treatment, respectively [43]. In the main stream, flocculants may be introduced for reducing a higher than average chemical oxygen demand and nutrient content in the influent of the biological treatment step. Increasing demands on the removal of organic trace substances and nutrients will potentially make the application of synthetic hydrophilic polymers in the WWTP's main stream more frequent in the future [43]. By contrast, the use of synthetic hydrophilic polymers is common practice in the WWTP's side stream. This typically results in residual flocculant

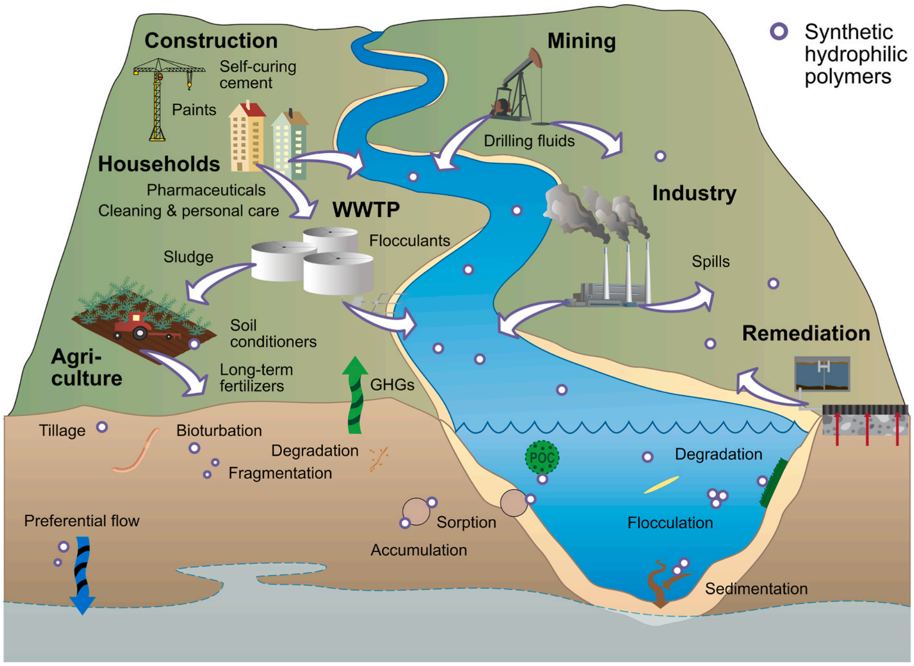


Fig. 2. Potential sources and fate of synthetic hydrophilic polymers in the environment (CC BY-SA 4.0, Integration and Application Network, https://ian.umces.edu/media-library).

concentrations of 5–20 g kg^{-1} dewatered sludge [7,43]. In addition, the sludge may contain other synthetic hydrophilic polymers removed during wastewater treatment. Rolsky and Kelkar [100] estimated that 60 % of the PVOH entering WWTPs in the United States end up in sewage sludge. If the sludge is not incinerated, it leaves the WWTP to be landfilled or applied to agricultural fields.

What remains in the treated wastewater is polymer residues. They may range between 4 and 15 % of the PEG (0.3 kDa) and PVOH, respectively, that initially entered the WWTP [99,100]. These residues are introduced into the receiving waterbody as part of the treated wastewater. For example, Antić et al. [26] detected 1–7 mg L^{-1} PVP in treated wastewater, which was diluted to 0.1 mg L^{-1} in the receiving river.

These findings suggest that more research is required to understand the processes in WWTPs better to achieve higher elimination rates of synthetic hydrophilic polymers. The development of alternative, ideally biodegradable flocculants could be instrumental to outperform stipulated minimum degradation rates of 20 % in two years as proposed in Germany, for instance Ref. [43]. Furthermore, the discharge characteristics of synthetic hydrophilic polymers during rain events need to be investigated.

4.3. Soil

Synthetic hydrophilic polymers may enter soil through agricultural activities, mining, soil remediation, and urban runoff. Their hydrophilic character allows them to dissolve or disperse in soil solution, enabling their distribution within the soil matrix. Yang et al. [101], for instance, found PAA at 60 cm soil depth after 8 years of soil conditioning of a sandy loam. Up to 16 % of low-molecular-weight PAA (<70 kDa) applied to the sandy topsoil of an outdoor lysimeter were eluted with percolate water [102]. Other studies suggested that synthetic hydrophilic polymers are rather immobile [17,103]: PAA (10–15 MDa), for instance, was observed to almost completely remain in the uppermost 2 cm of a column packed with silty clay and sandy loam at various soil water contents and salt levels of the irrigation water [104]. To the best of our knowledge, no experimental data exists for other synthetic hydrophilic polymers but their mobility is most likely determined by the polymer's molecular weight [105] and modulated by the soil texture and the presence of polyvalent ions. Synthetic hydrophilic polymers are assumed to sorb well to soil minerals and soil organic matter (SOM) via electrostatic and van der Waals forces. Sorption dynamics are controlled by the polarity, configuration, and size of a polymer as well as by the clay content and type, pH, ion composition, and ionic strength of the soil solution [17,106,107]. Desorption has rarely been observed for synthetic hydrophilic polymers, which is probably attributed to the high number of sorption sites along the polymer chain [107–110]. This could render soil a potential sink for synthetic hydrophilic polymers. On the contrary, weathering and polymer degradation may cleave the polymer chain favoring the desorption and remobilization of shorter chain fragments. Subsequent transport not only depends on the polymer's molecular weight, the soil texture, and ionic strength but presumably also on the soil porosity, the soil hydraulic conductivity, preferential flow paths, water saturation, and precipitation regimes. In addition, tillage or bioturbation may translocate synthetic hydrophilic polymers into deeper soil [101].

Biodegradation rates of synthetic hydrophilic polymers in soil depend on the polymer type and environmental conditions: while some polymers of low molecular weight biodegrade at noticeable rates, others are almost resistant to degradation and might accumulate in the long term [5,27,111]. PEG (4–6 kDa) and PVOH, for instance, were observed to degrade in soil by 5–10 % within 70 days [112,113]. By contrast, anionic PAM and PAA (6 kDa–15 MDa) only degraded by 5–10 % and <0.5 % per year, respectively [114,115]. Specialized fungi or bacteria may achieve a faster degradation [116,117], but such applications are typically restricted to laboratory conditions. For many synthetic hydrophilic polymers, including PVP and polyquaternium (PQ) salts, biodegradation rates have not been investigated [103]; and hardly any information is available on degradation processes under varying environmental conditions [8,16]. Additionally, abiotic processes such as hydrolysis, mechanical, chemical, thermal stress, as well as photodegradation contribute to the structural breakdown and fragmentation, and thereby further translocation and biodegradation [13,118]. Yet, hydrolytic and photolytic reactions are typically less relevant in soil and restricted to a few polymers like polycarboxylates and PEG [103].

It is pivotal to emphasize that the current knowledge of the degradation of synthetic hydrophilic polymers mostly comes from controlled laboratory studies [16,119]. More realistic mesocosm or field studies are utterly lacking. Future investigations on degradation dynamics should focus on investigating realistic environmental scenarios to gain a more comprehensive understanding of their fate in soil. Agricultural practices and extreme weather events like droughts and flooding need to be considered, particularly in the light of climate change scenarios. Further attention should be paid to degradation products of synthetic hydrophilic polymers that may exhibit higher mobility, bioavailability, and toxicity [4,8].

4.4. *Natural surface waters, sediment, and ground water*

Natural surface waters may receive synthetic hydrophilic polymers from WWTPs, stormwater runoff, and combined sewer overflows. They are suggested to preferentially sorb to sediments and suspended matter. This has been demonstrated for PEG (0.3 kDa), which was found sorbed at concentrations several orders of magnitude higher than in the free water phase [99]. Sorption is facilitated with increasing molecular weight of the polymer [120] but can be hampered by entangling of long polymer chains [103,121]. Among others, this may be the reason why sorption isotherms of synthetic hydrophilic polymer are often nonlinear [122]. Similar to soil and WWTPs, sorption to natural organic matter and sediment is further influenced by the polymers' physicochemical properties like their polarity. Amide groups, for instance, will undergo hydrogen bonds with suitable surface-active sites of organic and inorganic matter [123,124]. Anionic hydrophilic polymers are negatively charged and thus bind to positively charged mineral particles [125]. Ion bridges are probably further mediated by polyvalent ions [123]. In contrast, cationic hydrophilic polymers sorb to negatively charged surfaces from suspended particulate matter, dissolved organic matter and minerals in sediment [126–128]. Environmental parameters such as salinity have an additional impact on the molecular conformation of the polymer, reducing electrostatic repulsion and stimulating sedimentation of anionic hydrophilic polymers [129], whereas nonionic and cationic polymers are expected to be more insensitive to salinity changes [8].

The relevance of coagulation is underpinned by removal rates of up to 95 % of the PAA added in WWTPs [130]. It may be well assumed that flocculants, such as PAA, behave similarly in natural surface waters if concentrations are sufficiently high [131,132]. Ionic hydrophilic polymers would form insoluble complexes with polyvalent cations and negatively charged dissolved organic carbon. As a consequence, some synthetic hydrophilic polymers are not expected to be mobile in the environment while others are [17], an assumption that requires a systematic assessment.

As opposed to soil, synthetic hydrophilic polymers sorbed to sediment can desorb as shown for low-molecular-weight PEG (<3 kDa) [128]. Yet, PAA of similar molecular weight (4.5 kDa) rather accumulated in the upper layers of sand columns [133] or was removed from the surface of clay minerals by <3 % irrespective of the polymer's polarity [134]. These findings indicate a low risk of synthetic hydrophilic polymers with high molecular weight to reach groundwater [120] but hint at sediments as sinks of synthetic hydrophilic polymers. However, polymers of low molecular weight may be replaced by polymers of higher molecular weight at sorption sites [134], which could enable vertical transport of the former through sediments and soils towards groundwater bodies. Similarly, high-molecular-weight polymers probably degrade into smaller molecules promoting transport through sediment [135].

The biodegradation potential of synthetic hydrophilic polymers is considered rather low in natural waters [16,103]. Most synthetic hydrophilic polymers are too large for direct uptake and internal metabolization by microorganisms. They need to be broken down by exo-enzymes in a first step [103]. Low-molecular-weight PEG (<2 kDa), for instance, may be biodegraded in seawater by up to 90 % in 20 days, while higher molecular weights require more than 120 days to reach the same degradation level [136]. Similarly, PQs hardly biodegrade, which may partially be explained by their significant molecular weight (10–30 kDa) [103]. In freshwater systems, 1 kDa PEG was only degraded by 20 % after 135 days [102]. Degradation rates in sediments are presumed to fall into the same range given that PAAs in activated sludge were removed by 40 % after 90 days [102]. Besides the polymers' molecular weight, high initial concentrations have been found to decrease degradation rates [102], which points to potential adverse effects.

5. Potential impacts of synthetic hydrophilic polymers on ecosystem functions

5.1. *Soil structure and function*

As outlined in Section 3.4, synthetic hydrophilic polymers with superabsorbent properties are used as soil conditioners to improve the soil structural stability and reduce soil erosion [14,83,137] by agglutinating soil particles [138–141]. They store water, nutrients, and agrochemicals, which makes resource use more efficient, particularly in arid regions [137,142–144]. By increasing the proportion of water-stable aggregates, soil conditioners further facilitate the physical protection of SOM and hence decelerate SOM decomposition [101]. PAMs and PAAs added as sodium salts can increase soil pH upon exchange with protons and thus counteract soil acidification [145]. By creating such favorable conditions for plant and root growth, soils eventually become better aerated [142].

Despite the enormous research and development on synthetic hydrophilic polymers as water and nutrient retention agents, most studies focus on improving their material properties and function but neglect product safety and environmental implications [146]. Beneficial effects of synthetic hydrophilic polymers have mostly been reported from depleted soil, where field applications of a PAM-based soil conditioner (45 kg ha^{-1}) were shown to increase microbial enzyme activity after 9 years, for instance Ref. [147]. But there is hardly any information available on the toxicity of synthetic hydrophilic polymers to terrestrial organisms [103]. The few studies available mainly performed acute tests, and they did not observe any adverse effects towards soil respiration, earthworms, and crop productivity below 2.5 g kg^{-1}, 1 g kg^{-1}, and 225 mg kg^{-1} PAA (4.5–70 kDa, Fig. 3), respectively [102,103]. Long-term studies and toxicity tests scrutinizing indirect effects or other polymers than PAA are scarce. Moreover, assessing the environmental risk of synthetic hydrophilic polymers is challenged by a lack of monitoring studies and thus unknown concentrations in soil. However, predicted environmental concentrations (PECs) have been modeled for selected polymers: PEG was estimated at 13 μg kg^{-1} [8,148]; and PECs for PAA and PAM ranged from 3 to 1300 mg kg^{-1} for diffuse entries and may reach up to 9 g kg^{-1} close to point sources [8,148,149]. As most synthetic polymers are hardly biodegradable, such concentrations may cause unforeseeable side effects upon the continuous entry and accumulation of synthetic hydrophilic polymers in soil. For example, synthetic hydrophilic polymers used in construction act as pore-filling material and form natural cement [150]. Similar processes are likely to occur in natural systems, where synthetic hydrophilic polymers could clog soil pores and successively cement soil particles to form large, irreversible, and non-wettable structures [20,101,139]. This would decrease water infiltration and water availability with adverse consequences for soil organisms, soil quality, and plant growth [151,152]. In addition, some synthetic hydrophilic polymers may exert adverse effects when degrading into oligomers or by leaching of additives and non-intentionally added substances. This has been demonstrated for PAA releasing toxic acrylamide monomers under anaerobic conditions [153] and potentially affecting soil organisms and function [4,8].

Although the high sorption capacity of synthetic hydrophilic polymers is certainly beneficial for storing and controlling the release of water, soil nutrients, and agrochemicals, it may alter the fate of other

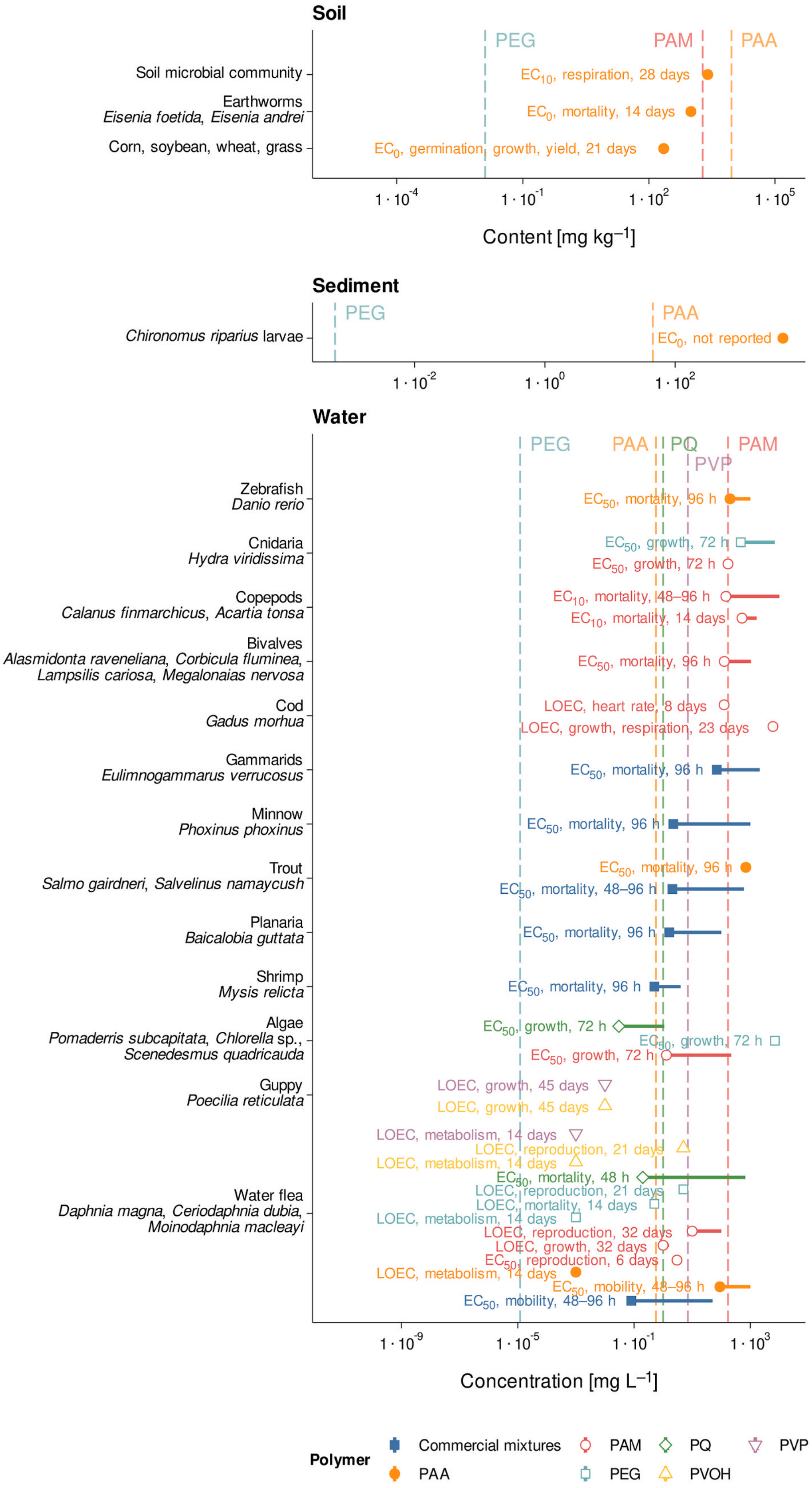


Fig. 3. Terrestrial and aquatic ecotoxicity of synthetic hydrophilic polymers; dashed vertical lines indicate maximum predicted environmental concentrations (PECs); EC = effect concentration, LOEC = lowest observed effect concentration, PAA = polyacrylate, PAM = polyacrylamide, PEG = polyethylene glycol, PQ = polyquaternium, PVOH = polyvinyl alcohol, PVP = polyvinylpyrrolidone; data compiled from Refs. [8,26,102,103,148,149,169–173,175–178,180–182,184].

pollutants upon changing environmental conditions. This has been shown for PEG- and polysorbate-based pesticide formulations mobilizing legacy DDT contaminations [154], which may pose a latent risk for soil quality and ecosystem functioning. However, little is known about the extent and reversibility of such remobilization processes, particularly upon degradation and dispersal of synthetic hydrophilic polymers.

5.2. Plant productivity

A recent meta-analysis of 310 scientific articles on the use of synthetic hydrophilic polymers with superabsorbent properties for soil conditioning revealed yield increases by up to 18 % for several crops [71]. The authors found that beneficial effects on plant productivity were mainly attributed to the polymer-mediated increase in water and nutrient availability. Soil conditioners reduce evapotranspiration and increase water retention in the rhizosphere. Nutrients are made available long-term by entrapment in the polymer's hydrogel network. Zheng et al. [71] concluded that the most beneficial and economic use of soil conditioners is for drought-sensitive plants in rainfed systems with low nitrogen content by application next to plant roots.

Yet, the effects of soil conditioners on crop yield and water retention remain inconsistent and vary with environmental and application conditions. A multitude of parameters influence their efficacy, including soil properties, physicochemical parameters of the polymer and the swollen gel, and their application method and rate [71,155]. Additionally, the effect of soil conditioners is expected to vary with crop type. Typically, potatoes and other vegetables are more sensitive to irrigation deficits than wheat or maize [71,156]. Although the application of soil conditioners is generally more beneficial in sand or clay soil than in loamy soils [155,157], the complexity of interactions between the parameters modulating their effect on crop yield makes it difficult to provide site-specific recommendations [158].

Long-term effects of synthetic hydrophilic polymers used for soil conditioning are scarcely investigated, but a gradual decline of their efficacy is likely [71,159]. Their effect may even become negative [160]. Werden et al. [159], for example, showed that the growth-supporting effects of a PAM–PAA copolymer ceased within two years after application. One reason for the limited effect of soil conditioners on crop yield is that the water stored by the polymer is not permanently available to plants. Shrinking of hydrated polymers upon drying may lead to a drop in water conductivity between the hydrogel and the rhizosphere, eventually reducing water exchange [161]. Insufficient water conductivity makes it difficult for roots to access the hydrogel-bound water, resulting in apparent water scarcity [162] and potential competition with other soil organisms.

While indirect effects of synthetic hydrophilic polymers from easily measurable entities like yield and crop productivity are well studied [71,163], direct effects on plants are still incompletely understood. There is evidence that the application of superabsorbent polymers may disturb the root ion balance leading to calcium deficiency and affecting cell viability. Chen et al. [164], for example, found maize root growth reduced and root morphology damaged during growth experiments in PAA. Cork oak (*Quercus suber*) and *Populus euphratica* seeds coated with PAA resulted in higher shoot growth but no differences in total biomass and a lower main root length, respectively [165,166]. Current literature thus indicates that synthetic hydrophilic polymers with superabsorbent properties induce morphological changes in plants. However, the mode of action is unclear and might differ among polymer types and plants.

5.3. Carbon and nitrogen cycling

According to Yang et al. [101], synthetic hydrophilic polymers protect SOM from microbial degradation by formation of water-stable aggregates. In this regard, synthetic hydrophilic polymers may have a similar function as clay minerals that govern the cohesion of soil particles as well as shrinking and swelling processes [141]. Given the increase in aggregate-protected SOM, it is likely that both organic carbon and nitrogen stocks are stabilized under the influence of synthetic hydrophilic polymers. Additionally synthetic hydrophilic polymers may promote soil microbial activity and thereby the conversion of fresh organic matter to SOM [167]. This suggests enhanced carbon sequestration, but at the same time the emission of greenhouse gases (GHGs) other than CO_2 may accelerate. Higher carbon and nitrogen availability at elevated water contents is the main prerequisite for N_2O emissions and decreased CH_4 uptake [168]. However, as long as soil conditioners are used under water-limited conditions, elevated CH_4 emission are less likely.

The final step of denitrification from N_2O to N_2 provides little energy to microbes and is therefore sensitive to changes in environmental conditions such as pH or water content [168]. If synthetic hydrophilic polymers interfere with this balance, this may impair denitrification and lead to higher N_2O emissions. To date, we are not aware of any scientific publication addressing the effect of synthetic hydrophilic polymers on GHG emissions. Similar to clay minerals, we assume that a slight positive effect of synthetic hydrophilic polymers on carbon sequestration will appear in the long term. However, negative climate effects due to increased N_2O emissions and a decreased CH_4 uptake probably prevail.

5.4. Aquatic ecotoxicity

Already in the 1970s, a first publication addressed flocculants for wastewater treatment: Biesinger et al. [169] assessed the acute toxicity of six commercial products containing PAM, PAA, PEG, and PQs towards rainbow trout, shrimp, and daphnids. In some cases, median lethal concentrations (LC_{50}s) were as low as 340 and 290 μg L^{-1} after 48 and 96 h, respectively. Chronic responses after 14 days of exposure were detected at concentrations below 60 μg L^{-1} for one of the products. Beim & Beim [170] elaborated on similar flocculant products and reported acute responses (LC_{50}s) after 96 h for planarians, daphnids, gammarids, and minnow ranging from 80 μg L^{-1} to more than 1 g L^{-1}. A prolonged 90-day vitality tests resulted in no observed effect concentrations as low as 0.001 μg L^{-1} for daphnids and 0.01 μg L^{-1} for algae (Fig. 3). These findings suggest a substantially higher sensitivity of daphnids compared to the other groups. Moreover, toxic effects were most likely induced by cationic rather than anionic or nonionic flocculants [170]. This may be explained by the electrostatic interactions between cationic hydrophilic polymers and negatively charged biological membranes [103], as observed in lake trout fry [171]. Linear anionic PAM showed an acute toxicity of 150 mg L^{-1} to *Daphnia magna* and adverse effects on reproduction and growth at 10 and 1 mg L^{-1}, respectively [172]. Similarly, Buczek et al. [173] reported 24–96 h LC_{50}s for three freshwater bivalves exposed to six non- and anionic commercial PAM products (5–17 MDa). In most cases, the LC_{50} was above 1 g L^{-1}, while for one of the PAMs (FLOPAM AN 923), LC_{50}s were as low as 0.1 g L^{-1}. Another study focusing on anionic PAM in oil-based, water-based, and solid products found acute effect thresholds for four out of the five tested products below 10 mg L^{-1}, in particular when oil-based PAM products were used [174]. This suggests that additives in the oil-based PAM products drove the toxicity rather than PAM itself. The rather low toxicity of PAM is consistent with reports from cod (*Gadus morhua*) observing changes in heart rates at concentrations above 100 mg L^{-1} but no effects on survival, growth, or respiration at concentrations up to 6 g L^{-1} [175]. Similarly, juvenile and adult copepods did not show lethal responses below 140 and 1000 mg L^{-1}, respectively [176]. More importantly though, the observed toxicity was mostly driven by the polymer's molecular weight, which the authors explained with an increased viscosity of the water phase and thus higher energy demands. Costa et al. [177] compared the toxicity of two cationic PAMs with different chain branching towards algae, daphnids, and bivalves. The more branched cationic PAM was generally less toxic to daphnids and bivalves, which may be attributed to the more compact molecules and the formation of aggregates reducing the interaction with organisms. With a median effect concentration of 1–35 mg L^{-1}, algae were indicated to be particularly sensitive to PAM irrespective of its molecular structure [177,178]. Another synthetic hydrophilic polymer applied to wastewater are cationic PQs like polydiallyldimethylammonium chloride (pDADMAC). With 320 μg L^{-1} pDADMAC, the 48 h LC$_{50}$ for *Ceriodaphnia dubia* was three orders of magnitude lower than for PAM. PQs may already affect algae in the low μg L^{-1} range by interfering with negatively charged cell membranes and inducing coagulation. Acute and chronic effect levels are similar for crustacea and fish but most likely driven by the binding of polymers to appendages or gills affecting mobility and oxygen uptake, respectively [103].

More recently, ecotoxicology started exploring potential effects of a wider set of synthetic hydrophilic polymers. For example, Nigro et al. [179] assessed the impact of PAA, PEG, and PVP on the survival, morphology, and behavior of zebrafish (*Danio rerio*). While acute responses were negligible for all three polymers, *D. rerio* behavior was significantly affected by PVP and PEG at 1 μg L^{-1} and PAA at 500 μg L^{-1}. In another study by Nigro et al. [180], exposure to 1 μg L^{-1} PAA, PEG, PVOH, and PVP affected the proteome, physiology, and behavior of *D. magna* after 14 days. PEG induced lethal effects at 0.5 mg L^{-1}. By contrast, acute and chronic toxicity of PEG, PAA, PVP, and PVOH towards *D. magna* did not show any effect even at 50 mg L^{-1}, the highest concentration tested by Mondellini et al. [181]. Only after 21 days, daphnid reproduction was affected at 5 mg L^{-1} PVOH and PEG. On the contrary, PAA and PVP did not affect reproduction but resulted in a higher number of reproductive cycles and body length at 10 mg L^{-1} [181]. In guppies (*Poecilia reticulata*), 10 μg L^{-1} PVOH and PVP (10 kDa) reduced growth during a 45-day exposure due to an increased energy demand [182]. The toxicity of PAAs probably stems from their chelating properties [103], while PEG induces oxidative stress and has some neurotoxic potential, as shown for tadpoles [103,183].

In comparison to the variety of ecotoxicity tests conducted in the free water phase, sediment-dwelling organisms have not been assessed systematically. In fact, there is only one study available that tested the acute toxicity of PAA (4.5 kDa, Fig. 3) during 96 h towards *Chironomus riparius* larvae. No significant effects were observed below the maximum test concentration of 4.5 g kg^{-1} [102]. Although this certainly requires further research, toxic effects may be limited given the high sorption capacity of synthetic hydrophilic polymers in porous media.

No comprehensive ecotoxicological risk assessment is publicly available for synthetic hydrophilic polymers to date [8]. PECs for surface waters range from 0.01 to 1 μg L^{-1} PEG and PQ to 77–150 μg L^{-1} PAM to 20–570 μg L^{-1} PAA [8,102,148]. Yet, PAM in seawater was detected at 170 mg L^{-1} [184], and PVP concentrations in WWTP effluent may reach 7.1 mg L^{-1} [26]. In sediments, environmental concentrations were estimated between 0.6 μg L^{-1} PEG and 12–45 mg L^{-1} PAA [8,148]. Given the effect concentrations reviewed above (Fig. 3) and the enormous quantity and diversity of synthetic hydrophilic polymers applied worldwide, these data call for precaution and further research.

6. Promising tools for assessing the fate and impact of synthetic hydrophilic polymers

6.1. Quantification in different matrices

Synthetic hydrophilic polymers are traditionally analyzed via reversed-phase liquid chromatography (LC), hydrodynamic chromatography, or size exclusion chromatography (SEC) coupled with UV or refractive index (RI) detectors [185–187]. Besides quantification, SEC provides additional information on the molecular weight of the polymer but may suffer from interferences with environmental matrices [178]. More recent approaches aim at hyphenating SEC and LC with mass spectrometry (MS) to achieve lower detection limits and enhance specificity compared to UV or RI detectors. For instance, Shi et al. [188] and Pauelsen et al. [189] quantified PEG and polypropylene glycol (PPG) in the low μg L^{-1} range using LC-MS/MS and SEC-MS, respectively, for pharmacokinetic studies and WWTP monitoring. LC coupled to an evaporative light scattering detector was applied for quantifying PVOH in the low mg L^{-1} in dietary supplement tablets [190]. And Viodé et al. [191] characterized high-molecular weight PAM (>1 MDa) using SEC with charge-detection MS.

Well-established methods in plastic pollution research like Fourier-transform infrared (FTIR) and Raman spectroscopy as well as pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) [192] will be probably adapted to synthetic hydrophilic polymers in the near term. Kaal et al. [193] already combined SEC with solvent-based Py-GC/MS for the online characterization of PEG–PPG and PS–PMMA copolymers. Py-GC/MS has further been used to quantify PVP, poly (N-vinyl)-caprolactam, and polyethyleneimine in wastewater samples at 1–10 μg L^{-1} [194] or PAM in sewage sludge with a detection limit of 250 mg kg^{-1} [195]. Due to the comparatively low thermal stability of hydrophilic polymers, the samples typically require pyrolysis temperatures ≤500 °C and additional derivatization using thermally assisted hydrolysis and methylation agents such as N,O-bis(trimethylsilyl) trifluoroacetamide, trimethylchlorosilane, or tetramethylammonium hydroxide [195,196]. However, studies investigating the influence of decomposition temperatures and the degree of hydrolyzation of PVOH during Py-GC/MS and thermogravimetric analyses indicated inconsistencies in polymer quantification and characterization [197,198].

While the reviewed methodical advances are certainly innovative, quantitative analyses of synthetic hydrophilic polymers in environmental matrices are still in the early stages of development and will require further refinement, validation, and standardization. In addition, methods for other synthetic hydrophilic polymers like PVP and PQs need to be developed. Ideally, this will result in robust methods for routine analyses which facilitate environmental monitoring and enable more comprehensive fate and effect studies.

6.2. Tracing of labeled polymers

Comprehensive assessments of the fate of synthetic hydrophilic polymers in the environment have been challenging in recent years due to analytical limitations. One of the most efficient approaches to trace compounds through different environmental compartments and to overcome detection limits is the labeling of polymers.

Radiolabeling a polymer provides an accurate and precise quantification in environmental, biochemical, and biomedical research. This has led to various studies where radiolabeled polymers were employed *in vivo*. For instance, ^{64}Cu, ^{99m}Tc, ^{177}Lu, and ^{223}Ra radionuclides were introduced to hydrophilic polymer-based nanoparticles in biomedical applications and therapy [199–201]. Environmental studies have been performed with ^{22}Na in soluble silica particles [202]. A both versatile and precise method for radiolabeling of polymers employs the ^{125}I nuclide [203].

In polymer chemistry, the most promising studies so far have involved the introduction of ^{14}C into the PAA backbone. For this, a ^{14}C-labeled monomer is (co-)polymerized into the desired polymer structure. Two pathways for the synthesis of labeled PAA were performed. First, commercially available 1-^{14}C-acrylic acid was used in the polymerization reaction. Second, acrylic acid monomers were synthesized using 2-^{14}C-labeled malonic acid. 2-^{14}C-labeled malonic acid was also used to generate a polymer where the ^{14}C label forms an integral part of the polymer backbone. The latter had the advantage of being more robust against decarboxylation upon degradation in natural environments [204–206]. ^{3}H-labeled PAA was synthesized by treating the polymer with tritium gas in the presence of a PdO catalyst [207]. Although radiolabeling would allow precise analyses of the fate of synthetic hydrophilic polymers, introducing sizable amounts of radioactive materials into the environment has its caveats. Using stable isotopes like ^{13}C or ^{15}N could be a viable alternative here [114,208].

The combination of polymers and dyes has gained interest in recent years as it provides materials for miscellaneous technical applications. For instance, dye-containing polymers are now widely applied in medicine and the chemical analysis of polymer traces. A comprehensive scope employing azo, triphenylmethane, indigoid, perylene, and anthraquinone dyes was given in wastewater analysis [209]. To monitor polymers in the environment, fluorophores have been chemically or physically attached to polymers. One strategy is to introduce aminofluorescein into PAA after treatment with trifluoroacetic acid. Aminofluorescein labeling was indicated to be a valuable alternative to the rather expensive and potentially hazardous radiolabeling [207].

In bioimaging, dye and fluorophore molecules are incorporated into biocompatible polymers [210]. For the synthesis, fluorophores were developed with adaptive reactive groups attached to the molecules. The most common groups include amines, carboxylates, isothiocyanates, activated ester moieties, as well as thiol and azide substituents. However, it was found that the attached fluorophore might change the properties of the polymers in terms of polarity and hydrophobicity [210]. Dyes typically attached to polymers are carbocyanines, for their high extinction coefficients, or benzopyrilium and xanthenes with an extended π electron system and donor-acceptor substituents [210,211].

The attachment of dyes to a polymer may be achieved by adsorption, which would not change the intrinsic properties of the polymer. However, to study synthetic hydrophilic polymers in the environment, a chemical linking of the dye to the backbone is preferable due to the stronger bond which prevents the dye from leaching. To this end, various methods to either copolymerize or graft the dye to the polymer have been reported [210] but may require further refinements for applications in environmental research.

6.3. *Environmental impact assessment*

Section 5.4 revealed a considerable number of ecotoxicological studies already available for aquatic organisms. Current evidence suggests that the physicochemical properties of synthetic hydrophilic polymers, first of all their molecular weight and polarity, determine their impact. However, multiple key questions remain that require a closer look for understanding the environmental risks of synthetic hydrophilic polymers better. This particularly applies to soil and sediment, where data are scarce. Moreover, most studies publicly available followed standard (eco)toxicity test guidelines that mainly target direct exposure. This ignores indirect effect pathways via soil, sediment, or food. At the same time, data concentrates on a few types of synthetic hydrophilic polymers. Previous scientific insights justified a focus on anionic hydrophilic polymers due to their electrostatic interaction with negatively charged biological membranes. While this prioritization was certainly relevant for direct effects, we lack understanding of more subtle and indirect effects over multiple generations of single species (adaptation), community shifts (selection), or implications on food webs and thus ecosystem functions like net primary production or organic matter breakdown [212].

Adaptation at the individual and population level [213] may be most efficiently studied using standard test organisms with a rather short generation time by using or expanding on currently employed protocols involving microorganisms, collembola, daphnids, or others [214,215]. This approach ensures easy, parallel, and relatively cheap experiments. For more complex communities like microbial biofilms, effects of synthetic polymers could be studied in submersed cultures in established airlift or stirred tank reactors [216] as wells as lab-scale bioreactors that may help to gain a deeper knowledge of interactions at cell surfaces and impacts on biosynthesis [217,218]. Polymer-induced changes in the community structure, food web interactions, and ecosystem functions may either be studied in isolation in laboratory-based microcosms or involving mesocosms. The latter are inherently more complex and will benefit from including stable isotope analyses [219] and molecular ecological techniques [220].

These considerations argue for a more comprehensive impact assessment of synthetic hydrophilic polymers. This not only applies to the impact of individual polymers but extends to joint effects in mixtures. How synthetic hydrophilic polymers interact with other stressors remains a significant challenge for ecotoxicological research and risk assessment.

7. Conclusions

As part of this review, we defined synthetic hydrophilic polymers as anthropogenic polymers capable of interacting with water through polar functional groups. Depending on the polymer's polarity, molecular weight, its degree of crosslinking, and environmental conditions, synthetic hydrophilic polymers are swellable, dispersible, or completely soluble in aqueous media.

Our review identified households, agriculture, and mining as the main sources of synthetic hydrophilic polymers in the environment. While the majority of synthetic hydrophilic polymers are expected to end up in sewage sludge, some portions are discharged to natural waterbodies. Direct use in agrochemicals, sewage sludge applications, and mining may lead to their release to soil. The current literature indicates a rather unquestioned use of synthetic hydrophilic polymers, focusing on beneficial effects but neglecting potential negative consequences.

Scientific knowledge of the fate of synthetic hydrophilic polymers across ecosystems is limited but their partitioning and distribution is most likely driven by the polymer's polarity and molecular weight. Sorption and coagulation emerged as the most probable processes shaping the fate of synthetic hydrophilic polymers in soil and water. Since biodegradation is generally slow, synthetic hydrophilic polymers probably accumulate in various environmental compartments. To understand the fate of synthetic hydrophilic polymers in the environment better, analytical techniques need to be developed for a wider range of synthetic hydrophilic polymers.

Although soil and sediment were identified as potential hotspots of synthetic hydrophilic polymers, ecotoxicity studies for these environmental compartments are scarce. With PECs partly exceeding adverse effect thresholds, current knowledge points to a certain risk of synthetic hydrophilic polymers to the receiving environment. However, most data originate from acute and short-term tests of single polymers. Long-term studies exploring chronic or indirect effects of a wider range of synthetic hydrophilic polymers and interactions with other pollutants on ecosystem quality and function are virtually missing. Due to the ubiquity of synthetic hydrophilic polymers and their potential for accumulation, the existing knowledge gaps call for precaution and further research.

A better comprehension of the fate and effects of synthetic hydrophilic polymers will inform risk assessment and management. The precautionary principle may suggest a timely inclusion of synthetic hydrophilic polymers in ongoing legislative efforts such as the plastics treaty by the UN Environment Assembly or REACH revisions [4,5]. To this end, anthropogenic polymers could be regulated as a whole. According to the zero-waste hierarchy, this would imply that preventing the production and use of synthetic hydrophilic polymers is prioritized over other options such as reduction, recycling, or recovery [221,222].

CRediT authorship contribution statement

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Writing – original draft, Investigation. **Heidrun Steinmetz:** Writing – review & editing, Writing – original draft, Investigation. **Hermann F. Jungkunst:** Writing – review & editing, Writing – original draft, Investigation. **Werner R. Thiel:** Writing – review & editing, Writing – original draft, Investigation. **Mirco Bundschuh:** Writing – review & editing, Writing – original draft, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Cooperation Fund for Sustainability Research of the Carl Zeiss Foundation and the research initiative “NanoKat” of the state of Rhineland-Palatinate.

Abbreviations

ABS	acrylonitrile butadiene styrene
EC	effect concentration
FTIR	Fourier-transform infrared
GHG	greenhouse gas
LC	liquid chromatography
LC50	median lethal concentration
LOEC	lowest observed effect concentration
MS	mass spectrometry
Mt	megatons
NOEC	no observed effect concentration
PA	polyamide
PAA	polyacrylate
PAM	polyacrylamide
pDADMAC	polydiallyldimethylammonium chloride
PDMS	polydimethylsiloxane
PE	polyethylene
PEC	predicted environmental concentration
PEG	polyethylene glycol
PET	polyethylene terephthalate
PGA	polyglycolic acid
PMMA	poly(methyl methacrylate)
PP	polypropylene
PPG	polypropylene glycol
PQ	polyquaternium
PS	polystyrene
PU	polyurethane
PVA	polyvinyl acetate
PVC	polyvinyl chloride
PVOH	polyvinyl alcohol
PVP	polyvinylpyrrolidone
Py-GC/MS	pyrolysis-gas chromatography/mass spectrometry
RI	refractive index
SBR	styrene-butadiene rubber
SEC	size exclusion chromatography
SOM	soil organic matter
WWTP	wastewater treatment plant

Data availability

No data was used for the research described in the article.

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